A Global General Equilibrium Model with US State-Level Detail for Trade and Environmental Policy Analysis—Technical Notes

Justin Caron and Sebastian Rausch

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A global general equilibrium model with US state-level detail for trade and environmental policy analysis—Technical notes

Justin Caron* and Sebastian Rausch*†

Abstract

The analysis of environmental or trade-related policies in the US requires a rich data set and model describing the trade patterns of US states with international partners. These technical notes describe the integration of US state-specific economic data within a GTAP-based international trade model. The benchmark data set consists of integrated data from the following sources: international trade data and production structures outside the US are taken from the GTAP data set, intra-national trade as well as state-level production are taken from the Minnesota IMPLAN Group data set, bilateral trade data between US states and international regions come from the Origin of Movement and State of Destination series from the US Census Bureau, and energy data are taken from the Department of Energy's State Energy Data System (SEDS). This data set is used to calibrate a general-equilibrium multi-sector, multi-factor and multi-household Armington trade model.

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1. INTRODUCTION

This technical note describes an integrated model of US and world trade as well as the assumptions embedded in the creation of the underlying benchmark dataset required for its calibration. Such a model allows for general equilibrium analysis requiring both a US and a global scale. The model has potential uses in a variety of policy-relevant fields in which international trade plays a role. By tracking bilateral trade between states and countries, one can explicitly predict the effects of a trade restricting or trade facilitating policy on a specific state or region of the US. Distributional effects can also be investigated thanks to the inclusion of different household classes and government agents.[1]

The benchmark data set is built from a number of distinct date sources. International trade data and production structures outside the US are based on Purdue University's GTAP7 data set, information on which can be found in Narayanan and Walmsley (2008). Intra-national trade as well as state-level production are based on the Minnesota IMPLAN Group data set, the implementation of which is similar to that of Rausch and Rutherford (2009). None of these data sets are freely available and must be purchased from their respective owners. Only modifications relative to the integration of the models will be documented here as to not unnecessarily duplicate information from the above-cited papers.

Technical considerations pertaining to the merging, integrating and balancing of different data sets are discussed in Section 5.

2. THE MODEL

This section presents the key features of a multi-commodity, multi-region static numerical general equilibrium model of the world economy with sub-national detail for the US economy.

Table 1. Indices and sets.

i,j	Sectors and goods
s	US regions
t	International regions
r	All regions
fr	Fossil resources

2.1 Production and transformation technologies

For each industry ($i = 1, \ldots, I$, $i = j$) in each region ($r = 1, \ldots, R$) gross output (Y_{ir}) is produced using inputs of labor (L_{ir}), capital (K_{ir}), natural resources including coal, natural gas,

[1] The data set and model described in this technical note has been applied to investigate carbon leakage from a sub-national, Californian climate policies. This study has been published as: *Leakage from Sub-national Climate Initiatives: The Case of California, The Energy Journal*, forthcoming, by Justin Caron, Sebastian Rausch, and Niven Winchester.

Table 2. Activity levels and prices.

Activity levels	
Y_{ir}	Production of variety of good i in region r
X_{ir}	Inter-industry intermediate demand for variety of good i in region r
C_{ir}	Private demand for good i in region r
I_{ir}	Investment demand for variety of good i in region r
G_{ir}	Government demand for variety of good i in region r
M_{ir}	Total imports for good i in region r
D_{ir}	Total domestic demand for variety of good i in region r
G_r	Total government demand in region r
U_r	Private utility
Prices	
p_{ir}^{Y}	Price of variety of good i in region r
p_{ir}^{D}	Price of domestic composite of good i in region r
p_{ir}^{M}	Price of imported composite of good i in region r
p_{ir}^{X}	Price of inter-industry (intermediate) output of good i in region r
p_{ir}^{C}	Price of good i for private demand in region r
p_{ir}^{I}	Price of good i for investment demand in region r
p_{ir}^{G}	Price of good i for government demand in region r
p_{r}^{G}	Price of composite government demand in region r
p_{r}^{l}	Wage rate in region r
p_{s}^{k}	Capital rental rate in international region t
p^{k}	Capital rental rate in the US
p_{ir}^{VK}	Price of vintage capital in sector i in region r
p_{fr}^{R}	Price of fossil fuel *fr* in region r

Table 3. Endowments and exogenous flows.

$\overline{K}_r$	Capital endowment for region r
$\overline{VK}_{ir}$	Vintage capital endowment for sector i in region r
$\overline{L}_r$	Time endowment of region r
$\overline{R}_{fr}$	Resource endowment of type *fr*
T_r	Transfer payments to households in region r
TAX_r	Tax revenue for government in region r
B_r	Initial balance of payments surplus or deficit in region r (Note that $\sum_r B_r = 0$)

crude oil, and land (R_{ir}), and produced intermediate inputs (X_{jir}):[2]

$$Y_{ir} = F_{ir}(L_{ir}, K_{ir}, R_{ir}; X_{1ir}, \dots, X_{Iir})\,. \tag{1}$$

We employ constant-elasticity-of-substitution (CES) functions to characterize the production technologies and distinguish six types of production activities in the model: fossil fuels (indexed by f); refined oil, electricity, agriculture, and non-energy industries (indexed by n). All industries are characterized by constant returns to scale (except for fossil fuels, agriculture and renewable electricity, which are produced subject to decreasing returns to scale) and are traded in perfectly competitive markets. Nesting structures for each type of production system are depicted in **Figures A 1-A 6**.

Fossil fuel f, for example, is produced according to a nested CES function combining a fuel-specific resource, capital, labor, and intermediate inputs:

$$Y_{fr} = \left[\alpha_{fr}\, R_{fr}^{\rho_{fr}^R} + \nu_{fr}\, \min\left(X_{1fr}, \dots, X_{Ifr}, V_{fr}\right)^{\rho_{fr}^R}\right]^{1/\rho_{fr}^R} \tag{2}$$

where α, ν are share coefficients of the CES function and $\sigma_{fr}^R = 1/(1-\rho_{fr}^R)$ is the elasticity of substitution between the resource and the primary-factors/materials composite. The primary factor composite is a Cobb-Douglas function of labor and capital: $V_{fr} = L_{fr}^{\beta_{fr}} K_{fr}^{1-\beta_{fr}}$ where β is the labor share.

We adopt a putty-clay approach to model capital adjustments. Under this approach, a fraction ϕ of previously-installed capital becomes non-malleable and frozen into the prevailing techniques of production. The fraction $1-\phi$ can be thought of as that proportion of previously-installed malleable capital that is able to have its input proportions adjust to new input prices. Vintaged production in industry i that uses non-malleable capital is subject to a fixed-coefficient transformation process in which the quantity shares of capital, labor, intermediate inputs and energy by fuel type are set to be identical to those in the base year:
$Y_{ir}^v = \min\left(L_{ir}^v, K_{ir}^v, R_{ir}^v; X_{1ir}^v, \dots, X_{Iir}^v\right)\,.$

In each region, a single government entity approximates government activities at all levels—federal, state, and local. Aggregate government consumption is represented by a Leontief composite: $G_r = \min(G_{1r}, \dots, G_{ir}, \dots, G_{Ir})\,.$

2.2 Consumer preferences

In each region r, preferences of the representative consumers are represented by a CES utility function of consumption goods (C_i), investment (I), and leisure (N):

$$U_r = \left[\mu_{cr}\min\left[g(C_{1r}, \dots, C_{Ir}), \min(I_{1r}, \dots, I_{Ir})\right]^{1/\rho_{cr}} + \gamma_{cr}\, N_r^{1/\rho_{cr}}\right]^{1/\rho_{cr}} \tag{3}$$

where μ and γ are CES share coefficients, $g(\cdot)$ is a CES composite of energy and non-energy goods, and the elasticity of substitution between leisure and the consumption-investment

[2] For simplicity, we abstract from the various tax rates that are used in the model. The model includes ad-valorem output taxes, corporate capital income taxes, payroll taxes (employers' and employees' contribution), and import tariffs.

composite is given by $\sigma_{l,r} = 1/(1-\rho_{cr})$. The function $g(\cdot)$, which is a CES composite of energy and non-energy goods, is depicted in **Figure A 6**. Aggregate investment is a CES composite of investment goods: $I_r = \min(I_{1r}, \ldots, I_{Ir})$.

2.3 Supplies of final goods and intra-US and international trade

With the exception of crude oil, which is modeled a homogeneous good, intermediate and final consumption goods are differentiated following the Armington assumption. Our Armington specification differentiates goods by local (within-state), domestic (within-US) and international origin in a three-level nesting structure.

For each demand class, the total supply of good i is a CES composite of a domestically produced variety and an imported one:

$$X_{ir} = \left[\psi^z \, \mathit{ZD}_{ir}^{\rho_i^D} + \xi^z \, \mathit{ZM}_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{4}$$

$$C_{ir} = \left[\psi^c \, \mathit{CD}_{ir}^{\rho_i^D} + \xi^c \, \mathit{CM}_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{5}$$

$$I_{ir} = \left[\psi^i \, \mathit{ID}_{ir}^{\rho_i^D} + \xi^i \, \mathit{IM}_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{6}$$

$$G_{ir} = \left[\psi^g \, \mathit{GD}_{ir}^{\rho_i^D} + \xi^g \, \mathit{GM}_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{7}$$

where Z, C, I, and G are inter-industry (intermediate) demand, consumer demand, investment demand, and government demand of good i, respectively; and *ZD*, *CD*, *ID*, *GD*, are domestic and imported components of each demand class, respectively. The ψ's and ξ's are the CES share coefficients and the Armington substitution elasticity between domestic (including local) and the imported varieties in these composites is $\sigma_i^D = 1/(1-\rho_i^D)$.

The domestic and internationally imported varieties are represented by nested CES functions. We replicate a domestic border effect within our Armington import specification by assuming that goods produced locally are closer substitutes than goods from other states. We include separate import specifications for US regions (indexed by $s = 1, \ldots, S$) and international regions (indexed by $t = 1, \ldots, T$). The imported variety of good i is represented by the CES aggregate:

$$M_{ir} = \begin{cases} \left[\left(\sum_s \pi_{ist} \, y_{isr}^{\rho_i^{RU}}\right)^{\rho_i^M/\rho_i^{RU}} + \sum_{t \neq r} \varphi_{itr} \, y_{itr}^{\rho_i^M}\right]^{1/\rho_i^M} & \mathit{if} \quad r = t \\ \left[\sum_t \varphi_{itr} \, y_{itr}^{\rho_i^M}\right]^{1/\rho_i^M} & \mathit{if} \quad r = s \end{cases} \tag{8}$$

where y_{itr} (y_{isr}) are imports of commodity i from region t (s) to r. π and φ are the CES share coefficients, and $\sigma_i^M = 1/(1-\rho_i^M)$ and $\sigma_i^{RU} = 1/(1-\rho_i^{RU})$ are the implied substitution elasticity

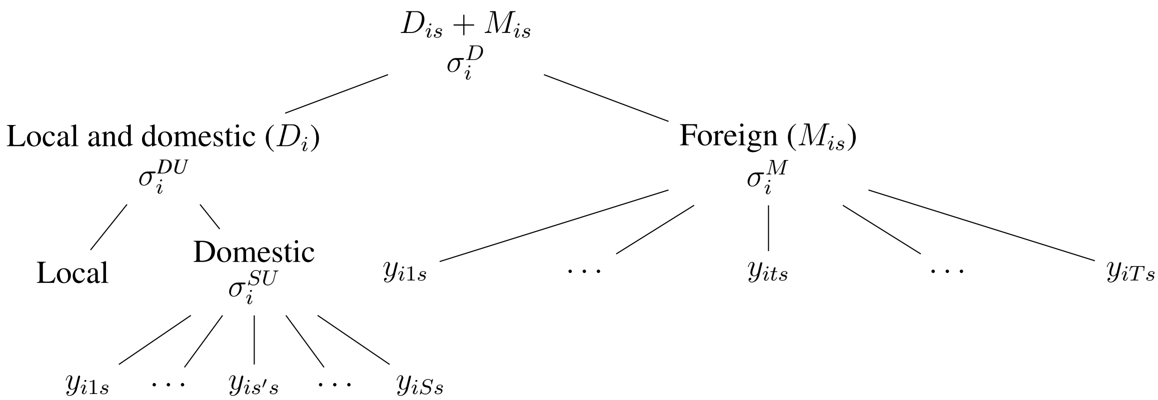

Figure 1. Aggregation of local, domestic, and foreign varieties of good i for US region s.

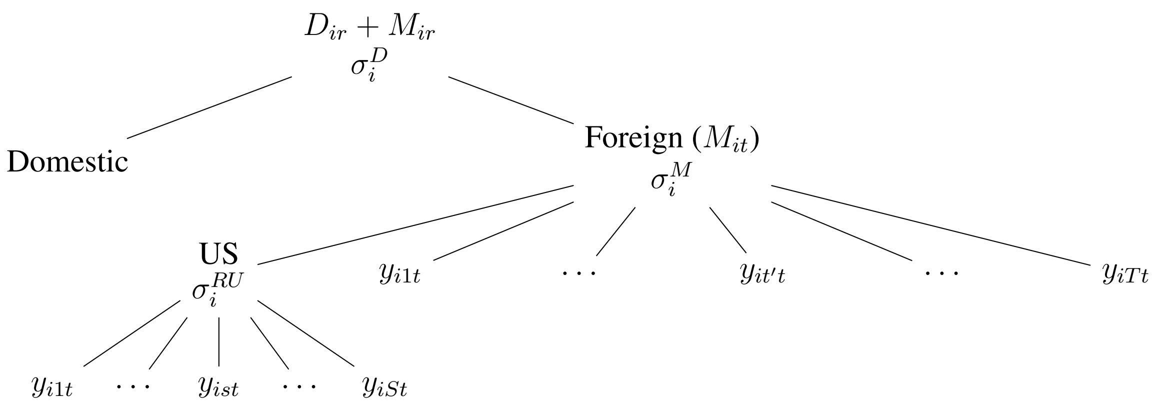

Figure 2. Aggregation of domestic and foreign varieties of good i for international region t.

across foreign and intra-US origins, respectively. The domestic variety of good i for US region s is represented by the CES aggregate:

$$D_{ir} = \begin{cases} \left[\left(\sum_{s \neq r} \pi_{isr} \, y_{isr}^{\rho_i^{SU}} \right)^{\rho^{DU_i}/\rho_i^{SU}} + \eta_{ir} \, y_i^{\rho_{ir}^{DU}} \right]^{1/\rho_i^{DU}} & \textit{if} \quad r = s \\ y_{ir} & \textit{if} \quad r = t \end{cases} \tag{9}$$

where η is a CES share coefficient, and $\sigma_i^{DU} = 1/(1 - \rho_i^{DU})$ is the implied substitution elasticities between the local variety and a CES composite of intra-US varieties. $\sigma_i^{SU} = 1/(1 - \rho_i^{SU})$ is the elasticity of substitution across US origins. **Figures 1** and **2** depict the nesting structures described by Eqs. (4)–(9).[3]

[3] There are three major interconnects of the power grid in the United States (Texas, Western, and Eastern interconnects), and very little trade is observed across these different interconnects. Our model approximates this case by not allowing trade in electricity between any two US regions that are not part of the same power grid system. Formally, we set the corresponding share parameters in the Armington CES functions equal to zero. Note that this also rules out positive trade flows in electricity across interconnects.

2.4 Emissions

Carbon emissions are generated according to the stoichiometry of fossil fuel combustion, which occurs in fixed proportions to the consumption of fossil fuels by industry and final demand sectors. The carbon emissions in region r are defined by the expression:

$$\text{Emissions}_r = \sum_f \kappa_f \left(Z_{ifr} + C_{fr}\right) \tag{10}$$

where κ_f is the carbon content.

2.5 Equilibrium, model closures, and model solution

Consumption, labor supply, and savings result from the decisions of the representative household in each region maximizing its utility subject to the budget constraint that consumption equals income:

$$\max_{\{C_{ir}, I_r, N_r\}} U_r \;\; s.t. \;\; p^i_r I_r + p^l_r N + \sum_i p^c_{ir} C_{ir} = p^k_r \overline{K}_r + \sum_i p^{VK}_{ir} \overline{VK}_{ir} + p^R_{fr} \overline{R}_{fr} + p^l_r \overline{L}_r + T_r \tag{11}$$

where p^i, p^c, p^k, p^{VK}, p^R, and p^l, are price indices for investment, labor services, household consumption (gross of taxes), capital services, rents on vintaged capital, and rents of fossil fuel resources. $\overline{K}$, $\overline{VK}$, $\overline{R}$, $\overline{L}$, and T are benchmark stocks of capital, vintaged capital, fossil fuel resources, labor, and transfer income.

Fossil fuel resources and vintaged capital are sector-specific in all regions. In international regions, malleable capital and labor are perfectly mobile across sectors within a given region but immobile across regions. In the US, malleable capital is perfectly mobile across US states and, as our model is intended to simulate a "medium-run" time horizon, we assume labor is mobile across sectors but not across states.

Given input prices gross of taxes, firms maximize profits subject to the technology constraints. Minimizing input costs per unit of output yields unit cost indices (marginal costs) p^Y_{ir} and p^{Yv}_{ir}. Firms operate in perfectly competitive markets and maximize their profit by selling their products at a price equal to these marginal costs.

The main activities of the government sector in each region are purchasing goods and services, income transfers, and raising revenues through taxes. Government income is given by: $GOV_r = TAX_r - T_r - B_r$, where TAX, T_r, and B are tax revenue, transfer payments to households and the initial balance of payments. Aggregate demand by the government is given by: $GD_r = GOV_r / p^G_r$ where p^G_r is the price of aggregate government consumption.

Market clearance equations for factors that are supplied inelastically are straightforward. The other market clearing equations are: (1) Supply to the domestic market equals demand by industry, household, investment, and government, (2) import supply of good i satisfies domestic demand by industry, household, investment, and government for the imported variety, (3) trade between all regions in each commodity is balanced, and (4) labor supply equals labor demand.[4]

[4] An appendix to this note provides a complete algebraic description of the equilibrium conditions of the model.

1. Supply to the domestic market equals demand by industry, household, investment, and government:

$$D_{ir} = ZD_{ir} + CD_{ir} + ID_{ir} + GD_{ir} \,. \tag{12}$$

2. Import supply of good i satisfies domestic demand by industry, household, investment, and government for the imported variety:

$$M_{ir} = ZM_{ir} + CM_{ir} + IM_{ir} + GM_{ir} \,. \tag{13}$$

3. Trade between all regions in each commodity is balanced:

$$\sum_s \sum_r y_{isr} + \sum_t \sum_r y_{itr} = \sum_s \sum_r y_{irs} + \sum_t \sum_r y_{irt} \,. \tag{14}$$

4. Labor supply equals labor demand.

Numerically, the equilibrium is formulated as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995). Our complementarity-based solution approach comprises two classes of equilibrium conditions: zero profit and market clearance conditions. The former condition determines a vector of activity levels and the latter determines a vector of prices. We formulate the problem using the General Algebraic Modeling System (GAMS) and use the Mathematical Programming System for General Equilibrium (MPSGE) (Rutherford, 1999) and the PATH solver (Dirkse and Ferris, 1995) to solve for non-negative prices and quantities.

3. DATA SOURCES

The benchmark data set contains economic data for all 50 US states, 112 world countries and regions (covering the whole world economy), and 53 sectors. It contains 3 factors of production, and for the US states, disaggregation into 10 distinct household types. It also includes a full bilateral trade matrix (including trade between US states, between US states and international trading partners, and between countries outside of the US).

This section discusses the data sources used for the model calibration in detail.

3.1 International economic data - GTAP

The implementation of international economic and trade data from the GTAP data set into a GAMS-based computable general equilibrium model is based on the GTAP7inGAMS framework described in Rutherford (2010). The Global Trade Analysis Project (GTAP) is a research program initiated in 1992 to provide the economic research community with a global economic data set for use in the quantitative analyzes of international economic issues. The project's objectives include the provision of a documented, publicly available, global, general equilibrium data base (See Narayanan and Walmsley (2008)). A list of applications based on the GTAP framework can be found at the GTAP home page, (HTTP://WWW.GTAP.ORG).

The GTAP version 7 database represents global production and trade for 113 country/regions, 57 commodities and 5 primary factors, two of which are “sluggish” (imperfectly mobile across sectors). The data characterize intermediate demand and bilateral trade in 2004, including tax rates on imports and exports and other indirect taxes. A guide to what’s new in GTAP7 can be found in Narayanan and Dimaranan (2008).

GTAP data is left mostly unchanged. A filtered version at the 0.001 tolerance level was used. A small aggregation of GTAP sectors is necessary to match the IMPLAN aggregation:

- Grains : GRN includes PDR,WHT,GRO
- Animal products nec : OAP includes OAP,RMK,WOL
- Crude oil and natural gas : CRU includes OIL,GAS

3.2 National economic data - IMPLAN

The implementation of the IMPLAN data into a GAMS-based computable general equilibrium is based on Rausch and Rutherford (2009). The IMPLAN (IMpact analysis for PLANning) data includes a set of benchmark economic data for the United States which covers each of the 50 states encompassing input-output tables with 509 commodities, nine classes of private households and six types of government agents. IMPLAN data is not freely available and must be obtained from Minnesota IMPLAN Group.

Comprehensive and detailed documentation of the IMPLAN data set—including definitions of accounts and the various types of data sources used for the construction of the data—is available on the web page of Minnesota IMPLAN group at www.implan.com. IMPLAN data is originally reported in $ millions, but is converted to $ billions in the data set.

3.3 Energy data

IMPLAN input output data is complemented by physical energy quantities and energy prices from the Department of Energy’s State Energy Data System (SEDS) for 2006 (EIA, 2009).

SEDS includes data for coal (col), refined oil (oil), electricity (ele), and natural gas (gas) and the following end-use sectors: ele Utilities, res Residential, com Commercial, ind Industrial, trn Transportation. These are mapped to the GTAP classification system.

Data extracted from SEDS includes:

- Energy prices, by state, source and end-use.
- Energy production, by state and commodity (in quantity terms).
- Energy consumption, by state and commodity (in quantity terms).
- Energy exports and imports, by state and commodity (in quantity terms).

We also include gasoline expenditure by state for own supplied household transportation from the 2006 EIA Gasoline Annual report. These data replace IMPLAN data when available.

3.4 Domestic US trade

Intra-national trade flows (trade between US states) are hard to measure, as there are no formal borders between states. We rely on a data set created by Lindall *et al.* (2006). They create a bilateral trade matrix for all sectors in IMPLAN by combining Commodity Flow Survey (CFS) ton-miles data for all sectors for which this data is available. Trade for other sectors is estimated in a gravity framework based on Oak Ridge National Labs (ORNL) county-to-county distances by mode of transportation data.

3.5 State to country bilateral trade data - Origin of Movement and State of Destination series

Bilateral trade flows between US states and countries are taken from the US Census Bureau's Foreign trade statistic State Data Series[5]. Export data is found in the Origin of Movement (OM) data series and import data is found in the State of Destination (SD) series. The OM series at state-level is available for all years since 1987, the data used here is from 2006 (to match IMPLAN). The import data in the state of destination series used is from 2008, the earliest available[6]. Both data sets are available at the detailed 6-digit HS classification level.

Table 4. Census bilateral trade data statistics.

	Import data	Export data
Year	2008	2006
# of HS6 sectors	5000	5178
# of countries	231	229
# of states or territories	54	54
Yotal value (bn USD)	97.4	204.4

The two series only include data on commodities, services are not described. To our knowledge, these two data sets have not received much attention in the economics literature. Several issues arise in the suitability of the data at accurately describe states of origin and destination.

3.5.1 Potential problems with OM and SD data

According to the Census Bureau, the Origin of Movement series provides export data "based on the state from which the merchandise starts its journey to the port of exports; that is, the data reflect the transportation origin of exports". The problem with the data series is that it does not necessarily represent production location (OP), the economic variable we are ultimately interested in. Cassey (2006) has done quite extensive diagnostic tests in order to assess whether or not the origin of movement can be considered to represent production location, using other "destination-less" estimates of state-level exports. He concludes that although "there are idiosyncratic sub-sectors and states, and systematic differences distinguishing the OM from OP", the data is of good enough quality to represent state of origin. He describes some systematic

[5] Description of this data can be found at http://www.census.gov/foreign-trade/aip/elom.html.

[6] The data has only been made available starting in 2010.

patterns in the OM data. Generally, he argues (as does the Census itself) that manufacturing sectors are more reliable, recommending the elimination of non-manufacturing sectors and to treat data for some specific sectors with caution[7]. He also warns that small states (Alaska, Hawaii, Delaware, Vermont) might suffer from bad data. More problematically, it is probable that states with important sea ports of exit (Florida, Texas, New York) might be overrepresented relative to their actual export specialization. There are other potential problems in the sectoral level of aggregation, as exports are classified using a commodity—rather than production—classification system. While we acknowledge these limitations to the data, we decide to keep all states and all sectors in the interest of build a comprehensive basis data set and argue that subsequent aggregation of sectors and states should smooth some of the irregularities out.

The import data in the State of destination series is even newer and has received little attention. The Census Bureau explains that the state of destination is defined as ”as the US state, US territory or US possession where the merchandise is destined, as known at the time of entry summary filing. If the contents of the shipment are destined to more than one state, territory, or possession, or if the entry summary represents a consolidated shipment, report the state of destination with the greatest aggregate value.” We assume that some of the same aggregation issues arise as with the OM data. Again, states with import ports of entry might be overrepresented.

Cassey (2010) provides an interesting descriptive overview and summary statistics revealed by the OM series.

3.6 US Census bilateral state-to-country trade data

Exports (Origin of movement) are from 2006, Imports (state of destination) from 2008 (earliest available data). The data contain two types of imports: general and consumption. These are described as:

- General: General Imports measure the total physical arrivals of merchandise from foreign countries, whether such merchandise enters consumption channels immediately or is entered into bonded warehouses or Foreign Trade Zones under Customs custody.
- Consumption: Imports for Consumption measure the total of merchandise that has physically cleared through Customs either entering consumption channels immediately or entering after withdrawal for consumption from bonded warehouses under Customs custody or from Foreign Trade Zones.

These two values are almost identical: totals are 2.10e12 vs 2.09e12. General imports are used.

State mapping Three US regions in the Census Bureau data are not in the IMPLAN list of states (PR - Puerto Rico, VI - Virgin Island and XX - unknown). Their shares of trade are small and are dropped. Their shares were:

[7] printing and publishing (323), chemicals (325), machinery (333), computers and electronic products (334), and transportation equipment (336)

Table 5. Missing regions.

Share	of exports	of imports
XX	0.035	0.011
PR	0.015	0.009
VI	0.00057	0.008

Country mapping Census data is available for 202 Census 4-digit country codes. They have been mapped to the 113 GTAP7 regions using the following mappings:

- GTAP to ISO3 (from: http://www.cepe.ethz.ch/people/profs/thomarut/gtaptools/gtap7regions.html)
- ISO3 to ISO2 (from: http://www.unc.edu/ rowlett/units/codes/country.htm)
- ISO2 to CENSUS (from: Census Bureau http://www.census.gov/foreign-trade/schedules/c/country.txt)

Not all countries could be mapped and there have been some (small) manual corrections.

Sector mapping The data use two variants of the HS6 classification. Census import data uses the ”2010 HTS record” classification. Export data uses the 2010 Schedule B record. Mapping was done using a HS2002 to GTAP mapping[8]. The mapping contains 44 of the 57 GTAP sectors (the commodities). 12 of the HS6 codes in census exports are missing from this mapping, as are 258 of the import codes. Of these, 28 are not in the Census' own mapping file. All these sectors are mapped to their nearest neighbor. A manual check of labels confirms that all seem to map to correct GTAP sector.

3.6.1 Descriptive statistics

The value-added of the Census OM and SD series is in painting a more precise picture of trade patterns by trading partner. We analyze here to which extent the data help describe the heterogeneity in these patterns. For this, we calculate the normalized relative specialization in trade by partner. Defining $IM_{i,r,s}$ as import flows from international region r to state s, we get (the same is done for exports):

$$\textit{IMspecialization}_{i,s,r} = \frac{IM_{i,r,s}}{\sum_s IM_{i,r,s} \frac{\sum_r IM_{i,r,s}}{\sum_{s,r} IM_{i,r,s}}} . \tag{15}$$

Figures 3 and **4** display these ratios for imports of energy intensive goods and exports of agricultural goods. A value of one implies no relative specialization of trade with the partner relative to the state's share of total US exports. As can be seen, there is considerable variability in the ratios, which illustrates the importance of the Census OM and SD series. It can clearly be

[8] This data is available at: https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=1916.

seen, for example, that manufacturing imports to California are biased towards regions to its west, whereas the eastern states import relatively more from Europe, the middle east and Russia.

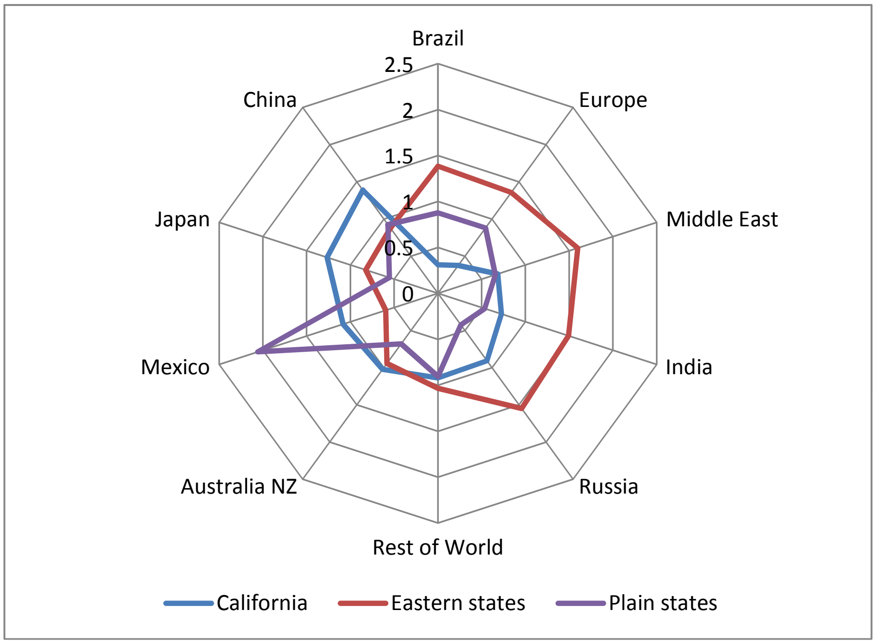

Figure 3. Distribution ofsources, Manufacturing (MAN) imports.

4. ELASTICITY PARAMETERS

Table 6 describes the set of Armington trade elasticities in the model.

Fossil fuel production levels are determined by the price of fuel relative to the price of domestic output. The production of fuel f requires inputs of domestic supply (e.g., labor and intermediate inputs) and a fuel-specific resource. Given the form of the production function in Eq. (2), the elasticity of substitution between the resource and the rest of inputs in the top nest determines the price elasticity of supply (ζ_f) at the reference point according to:

$$\zeta_f = \sigma^R_{fr} \frac{1 - \alpha_{fr}}{\alpha_{fr}} \,. \tag{16}$$

The imputed returns to the exhaustible resource are then netted out from the rental value of capital input in the database. Price elasticities of supply are taken from Paltsev *et al.* (2005). We employ $\zeta_{\text{COL}} = \zeta_{\text{GAS}} = 1$ and $\zeta_{\text{CRU}} = 0.5$. In a similar fashion, we calibrate the substitution elasticity between the value-added composite and the sector-specific resource factor for generation from nuclear sources ($\zeta_{\text{NUC}} = 0.25$). We set $\zeta_{\text{NUC}} = 0$ for all US regions reflecting our assumption that nuclear cannot expand above current levels, which we believe is consistent with current political realities and with the 10-year horizon of our analysis. The supply response of our renewable electricity is calibrated by setting ζ_{RNW} equal to the generation-weighted average of own-price supply elasticities for hydro and renewable electricity, where weights for generation by source are derived from EIA (2009). Following Paltsev *et al.* (2005), we set the own-price elasticities of supply from hydroelectricity to 0.5.

Table 6. Reference values of substitution elasticities in production and consumption.

Parameter	Substitution margin	Value
σ_{en}	Energy (excluding electricity)	1.0
σ_{enoe}	Energy—electricity	0.5
σ_{eva}	Energy/electricity—value-added	0.5
σ_{va}	Capital—labor	1.0
σ_{klem}	Capital/labor/energy—materials	0
σ_{cog}	Coal/oil—natural gas in ELE	1.0
σ_{co}	Coal—oil in ELE	0.3
σ_{rnw}	Resource—Capital/labor/energy/materials in renewable ELE	*Calibrated*
σ_{nr}	Resource—Capital/labor/energy/materials in nuclear ELE	*Calibrated*
σ_{am}	Materials in AGR	0
σ_{ae}	Energy/electricity—materials in AGR	0.3
σ_{er}	Energy/materials—land in AGR	0.6
σ_{erva}	Energy/materials/land—value-added in AGR	0.7
σ_{rklm}	Capital/labor/materials—resource in primary energy	0
σ_{gr}	Capital/labor/materials—resources	*Calibrated*
σ_{govinv}	Materials—energy in government and investment demand	0.5
σ_{ct}	Transportation—Non-transport in private consumption	1.0
σ_{ec}	Energy—Non-energy in private consumption	0.25
σ_{c}	Non-energy in private consumption	0.25
σ_{ef}	Energy in private consumption	0.4
σ_{l}	Leisure—material consumption/investment	*Calibrated*
σ_i^D	Foreign—domestic (and local)	GTAP, version 7
σ_i^M	Across foreign origins	GTAP, version 7
σ_i^{SU}	Across US origins for US regions	$1-\delta+\delta\sigma_i^M$
σ_i^{RU}	Across US origins for international regions	$1-\delta+\delta\sigma_i^M$
σ_i^{DU}	Local—domestic for US regions	$\sigma_i^{SU}\,/\,2$

Note: Unless otherwise stated, parameter values for the base case are taken from Paltsev *et al.* (2005). Substitution elasticity for fossil fuel, and nuclear resource factors are calibrated according to Eq. (16) using the following estimates for price elasticities of supply: $zeta_{\text{COL}} = \zeta_{\text{GAS}} = 1$, $\zeta_{\text{CRU}} = 0.5$, and $\zeta_{\text{NUC}} = 0.25$. σ_l is calibrated assuming that the compensated and uncompensated labor supply elasticity is 0.05 and 0.3, respectively.

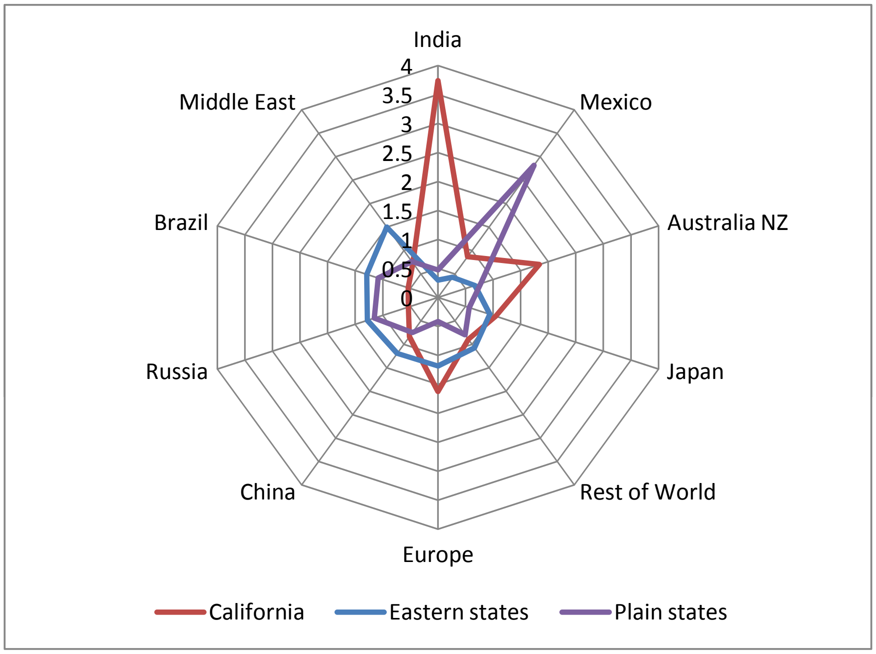

Figure 4. Distribution of sources, Agriculture (AGR) exports.

Labor supply is determined by the household choice between leisure and labor. We calibrate compensated and uncompensated labor supply elasticities following the approach described in Ballard (2000), and assume that the uncompensated (compensated) labor supply elasticity is 0.05 (0.3).

4.1 Trade elasticities

Substitution margins between international origins (σ_i^M) are taken from Hertel *et al.* (2007). The elasticity of substitution between foreign and domestic goods (σ_i^D) are taken from GTAP which sets them to be about half of σ_i^M. This 'rule of two' is, to the best of our knowledge, used in all two-nested Armington models. It is validated in Liu, Arndt and Hertel (2004) in a back-casting exercise.

As mentioned in the current draft of the paper, the international trade literature has long recognized the existence of a strong "international border effect". This effect has implicitly been modeled in many Armington-type models by using a two-tier nest distinguishing the trade-off between domestic and international sources. We use a similar strategy in order for our model to replicate a "domestic border effect".

One of our model's main contributions is the description of both domestic (within-US) and international trade. Modeling domestic trade requires additional response parameters in σ_i^{RU}, σ_i^{DU} and σ_i^{SU}. There are, to our knowledge, no available econometric estimates of these elasticities. Indeed, estimating σ_i^{SU} in the way done in Hertel would require exogenous data on trade costs (transport costs, since there are obviously no tariffs within the US) and we are not aware of the availability of any such data.

However, we do know from the gravity-equation based trade literature that there is also a domestic (or intrantional) border effect. Indeed, despite the fact there are no of formal trade barriers between states, there is a large significant impact of states barriers in reducing trade flows. This can be explained by the extreme ”localness” of trade, something which we want our model to replicate. This effect is generally estimated within a gravity framework, which estimates border dummies in a log-linear regression with exporter and importer fixed effects and controls for distance and other bilateral trade costs.

Strong evidence that state borders also reduce trade flows was first found by Wolf (2000). However, he does not include international trade data and thus cannot compare the strength of this effect to that of the international border. Coughlin and Novy (2011) include both domestic trade and international trade flows, and find the domestic border effect not only to be significantly different from zero, but also to be larger than the international border effect by a factor of about two. This might seem surprising but reveals that most trade is indeed very “local”. This fact is confirmed in the Brazilian context by Fally *et al.* (2010).

Since we do not have disaggregated estimates of the domestic elasticity of substitution, our strategy has been to focus on the relative strength of the international and domestic border effects. We argue that it can be approximated by adjusting the relative values of σ_i^M (for which we have estimates by sector) and σ_i^{SU}, thus allowing domestic goods to be closer substitutes to each other than international goods. This allows the import demand elasticities from domestic goods (from other states) to be higher than those of international goods.

To do this, we rely on the border effect estimates from Coughlin and Novy (2011) as they use the same trade data sets as we do (the commodity flow survey for domestic trade and the origin of movement series for state-to-country trade) which makes their estimates relevant to our calibration. They estimate the coefficient on the international border dummy, $\beta = (1-\sigma)\widetilde{\beta}$, to be -1.1[9] and the coefficient on the international border dummy, $\gamma = (1-\sigma)\widetilde{\gamma}$, to be -2.05. Given the lack of observable trade costs, the effect of the elasticity of substitution σ cannot be distinguished from the true border effect $\widetilde{\beta}$. However, it does allow identification of the relative strength of these coefficients (denoted here as δ):

$$\delta = \frac{(1-\sigma)\widetilde{\beta}}{(1-\sigma)\widetilde{\gamma}} = \frac{\widetilde{\beta}}{\widetilde{\gamma}} = 1.864 \tag{17}$$

Our Armington model does not include trade costs[10], but does allow for different Armington elasticities of substitution and thus trade elasticities (the trade elasticity in gravity models is $1-\sigma$, where σ corresponds to the Armington elasticity). Thus, we can introduce δ in our model by varying the ratio of the Armington elasticity of domestic substitution σ_i^{SU} to that of

[9] Changing the reference point (where both dummies are zero) from domestic trade to international trade.

[10] It does include transport margins.

international substitution σ_i^M, such that:

$$\delta = \frac{(1 - \sigma_i^{SU})}{(1 - \sigma_i^M)} = 1.864 \tag{18}$$

Using estimates of σ_i^M from Hertel *et al.* (2007), we can thus back out σ_i^{SU}. This calibration procedure implicitly assumes that δ is identical across sectors. Similar to σ_i^D, σ_i^{DU} is set to be half the value of σ_i^{SU}.

Table 7 displays these elasticity parameters by sector.

Table 7. Armington Elasticity Parameters in Model.

σ	M	D	SU	DU
TRN	3.8	1.9	6.2	3.1
SRV	3.8	1.9	6.2	3.1
OIL	4.2	2.1	7.0	3.5
AGR	4.9	2.5	8.3	4.2
EIS	5.5	2.6	9.4	4.7
ELE	5.6	2.8	9.6	4.8
GAS	5.6	2.8	9.6	4.8
NMM	5.8	2.9	9.9	5.0
PPP	5.9	3.0	10.1	5.1
I_S	5.9	3.0	10.1	5.1
COL	6.1	3.0	10.5	5.3
CRP	6.6	3.3	11.4	5.7
MAN	8.2	4.0	14.3	7.2
NFM	8.4	4.2	14.8	7.4
CRU	13.9	7.3	25.1	12.5

5. DATA MERGING AND BALANCING

This section describes technical issues in merging and balancing the datasources. **Table 8** displays the set structure of the benchmark data set. **Table 9** describes the parameters. **Table 10** describes the variables and associated prices in the model.

The calibration strategy is now presented in some detail. The international economic data as well as trade data from GTAP is left unchanged. Each state's share of trade (with each partner) is adjusted using data from the Census Bureau, and national economic data from IMPLAN is re-balanced to obtain a micro-consistent data set. The resulting data set is based on an adaptation of the GTAPinGAMS namespace. The following steps have been undertaken to integrate the different data sets:

1. Import IMPLAN data and bilateral intra-national trade data and modify name set;
2. Aggregate IMPLAN to GTAP aggregation level;

Table 8. Set Indices and Elements.

Set			**Elements**	**Description**
i				Sectors
f				**Factors of production**
			cap	Capital
			lab	Labor
			natres	Natural resources (GTAP regions only)
			land	Land (GTAP regions only)
g				**all end use (i, c, p, i)**
	c			
		h		**Households**
			hhl	Households <10k (10001)
			hh10	Households 10-15k (10002)
			hh15	Households 15-25k (10003)
			hh25	Households 25-35k (10004)
			hh30	Households 35-50k (10005)
			hh50	Households 50-75k (10006)
			hh75	Households 75-100k (10007)
			hh100	Households 100-150k (10008)
			hh150	Households >150k (10009)
		"c"		Private consumption in GTAP regions
	p	**pub**		**public (govt) institutions**
			fnd	Federal Government NonDefense (11001)
			fdf	Federal Government Defense (11002)
			fin	Federal Government Investment (11003)
			sln	State Local Govt NonEducation (12001)
			sle	State Local Govt Education (12002)
			sin	State Local Govt Investment (12003)
		"g"		govt consumptino in GTAP regions
	i			
		corp		**corporate institutions**
			ent	Enterprises (Corporations) (13001)
			inv	Gross Private Fixed Investment (Capital) (14001)
			stk	Inventory Sales Deletions (14002)
		"i"		Investment
t				**An aggregation of 45 IMPLAN accounts**
s				**An aggregation of 50 US states**
r				**An aggregation of the 112 int l GTAP regions**
rs				**States and regions combined**

Table 9. Parameter Description.

Parameter	US state only	Description
vfm(f,g,rs)		Endowments - Firms' purchases at market prices
vdfm(i,g,rs)		Domestic purchases at market prices
vifm(i,g,rs,trd)		Imported purchases at market prices
vxmd(i,rs,rsrs)		Trade - bilateral exports at market prices
evom(f,rs,corp,t)		Factor supply
rto(g,rs)		Output (or income) subsidy rates
rtf(f,g,rs)		Primary factor and commodity rates taxes
rtfd(i,g,rs)		Firms domestic tax rates
rtfi(i,g,rs)		Firms' import tax rates
rtxs(i,rs,rsrs)		Export subsidy rates
rtms(i,rs,rsrs)		Import taxes rates
vst(i,rs)		Trade - exports for international transportation
vtwr(i,j,rs,rs)		Trade - Margins for international transportation at world prices
vinv(s)	√	Aggregate investment
evpm(s,j,g)	√	Goods supply (make and export)
vprf(s,g)	√	Corporate profit
vtrn(s,g,t)	√	Inter-institutional Transfers
vb(rs)		Current account balance
nt(s)		Net transfers

Table 10. Model Variables and Prices.

Variable	Dimension	Benchmark value	Description
Y	g,rs	vom(g,rs)	Supply
A	i,rs	vam(i,rs)	Armington composite supply
M	i,rs	vim(i,rs,"ftrd")	Imports from international sources
MUSA	i,rs	vim(i,rs,"dtrd")	Imports from US states
YT	j	vtw(j)	Transportation services
CE	rs		Carbon emissions
FSUP	f,g,rs		Factor supply by income class
P	g,rs	vom(g,rs)	Domestic output price
PA	i,rs	vam(i,rs)	Armington composite price
PM	j,rs	vim(j,rs,"ftrd")	International import PMUSAprice
PMUSA	i,rs	vim(i,rs,"dtrd")	Import price from US sources
PT	j	vtw(j)	Transportation services
PF	f,rs		Primary factors rent
PCARB	rs	co2lim(rs)	Shadow price of carbon
PTCARB			Traded carbon prices
PFS	f,g,rs		Household-specific factor rents
PTAX	rs		Tax revenue market

Table 11. Elasticities.

Parameter	Description
esub(g,rs)	Top-level elasticity (energy versus non-energy)
esubn(g,rs)	Top-level elasticity (among non-energy goods)
esubkl(g,rs)	Capital-labor elasticity
etrae(f)	Elasticity of transformation
esubd(i)	Armington substitution between domestic and imported goods
esubm(i)	Intra-import elasticity of substitution,
esubmusa(i,rs)	substitution between US sources
esubdusa(i)	substitution between local and domestic imports

3. Merge IMPLAN data, GTAP and Census international trade data;
4. Aggregate to any desired aggregation; and
5. Assign trade flows, compute intermediate parameters, and balance complete data set.

Thus, aggregation is undertaken before re-balancing.

5.1 Assigning trade

Aggregate trade flows to and from the US are described in the three independent data sources. **Table 12** summarizes these data according to their dimension.

Table 12. Available Trade Data (I=Sector, R=Country, S=State).

Data	Dimension	Year	Parameter
IMPLAN	I,S	2006	$EX\_IMPLAN(i,s)$ and $IM\_IMPLAN(i,s)$
GTAP	I,R	2004	$EX\_GTAP(i,r)$ and $IM\_GTAP(i,r)$
US bilateral trade	I,S	2007	..
CENSUS - exports	I,S,R	2006	$EX\_CENSUS(i,s,r)$
CENSUS - imports	I,S,R	2008	$IM\_CENSUS(i,s,r)$

Sectors with bilateral trade data from Census. We calculate each state's share of imports and exports using Census data as such:

$$\alpha^{EX}_{Census}(i,s,r) = EX\_CENSUS(i,s,r)/\sum_s EX\_CENSUS(i,s,r)$$

$$\alpha^{IM}_{Census}(i,s,r) = IM\_CENSUS(i,s,r)/\sum_s IM\_CENSUS(i,s,r)\,.$$

Bilateral trade is then assigned as such:

$$EX(i,s,r) = \alpha^{EX}_{Census}(i,s,r) \times EX\_GTAP(i,r)\,.$$

Sectors with no bilateral trade data. Of the sectors in the GTAP classification, the following are not represented in the Census data. Sectors with no export data: ELY, WTR, CNS, TRD, OTP, WTP, ATP, CMN, OFI, ISR, OBS, ROS, OSG, DWE. Sectors with no import data: WTR, CNS, TRD, OTP, WTP, ATP, CMN, OFI, ISR, OBS, ROS, OSG, DWE.

For these sectors, we use the following shares from IMPLAN:

$$\alpha^{EX}_{Implan}(i,s) = EX\_IMPLAN(i,s) / \sum_s EX\_IMPLAN(i,s)$$

$$\alpha^{IM}_{Implan}(i,s) = IM\_IMPLAN(i,s) / \sum_s IM\_IMPLAN(i,s)\,.$$

Bilateral trade is then assigned as such:

$$EX(i,s,r) = \alpha^{EX}_{Implan}(i,s) \times EX\_GTAP(i,r)\,.$$

Sectors with no trade data in IMPLAN, but non-zero trade in GTAP. The GAS sector has no import data in IMPLAN. In this case the trade shares from IMPLAN above are replaced by state shares of GDP. Thus in all cases trade totals, by destination country, will match GTAP totals.

5.2 Trade total comparisons

Table 13 gives an overview of how the different data sets match up. **Figures 5** and **6** compare import and export totals from the different data sources at the 10-sector aggregation level. Analogous graphs displaying the deviations for all GTAP sectors can be found at the end of the document in **Figures ??** and **??**. The data sets correspond to different years. To facilitate comparison, they have all been rescaled to match 2004 totals from GTAP7. The remaining differences stem both from different data collection methods and potentially bad sectoral mapping.

Table 13. Correlations between Competing Data Sets.

Dimension	Value	Aggregation	Data sets	Correlation	Spearman rank corr.
Sectors	Exports	53 sector GTAP	Census vs GTAP	0.9543	0.9768
Sectors	Exports	53 sector GTAP	IMPLAN vs GTAP	0.8121	0.7908
Sectors	Imports	53 sector GTAP	Census vs GTAP	0.9212	0.9658
Sectors	Imports	53 sector GTAP	IMPLAN vs GTAP	0.7813	0.68
Sectors	Exports	10 sector aggr	Census vs GTAP	0.9904	1
Sectors	Exports	10 sector aggr	IMPLAN vs GTAP	0.9991	1
Sectors	Imports	10 sector aggr	Census vs GTAP	0.9798	1
Sectors	Imports	10 sector aggr	IMPLAN vs GTAP	0.9155	0.7
Countries	Exports	113 GTAP regions	Census vs GTAP	0.981222	0.9474

How good the data set seem to match obviously depends on the aggregation level, as most of the substantial variations observed at the GTAP level are smoothed out by aggregation. Still, some large variations remain: the rapidly increasing price of crude oil between 2004 and 2006 increases the import value in the IMPLAN and Census data sets relative to GTAP. Also, the figures reveal missing Census SD data for imports of services (SRV) and transport (TRN), as well as missing IMPLAN data for imports of services.

Figure 7 displays the deviations at the destination-country level (for the 50 largest trading partners). Across this dimension, the mapping appears to be relatively good.

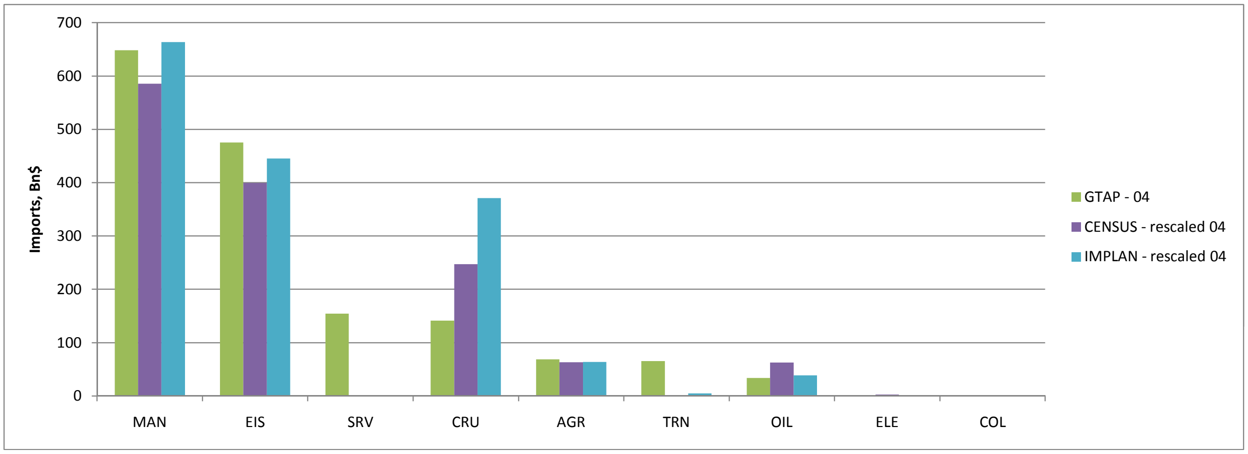

Figure 5. Imports - Deviations between data sets: 10-sector aggregation level

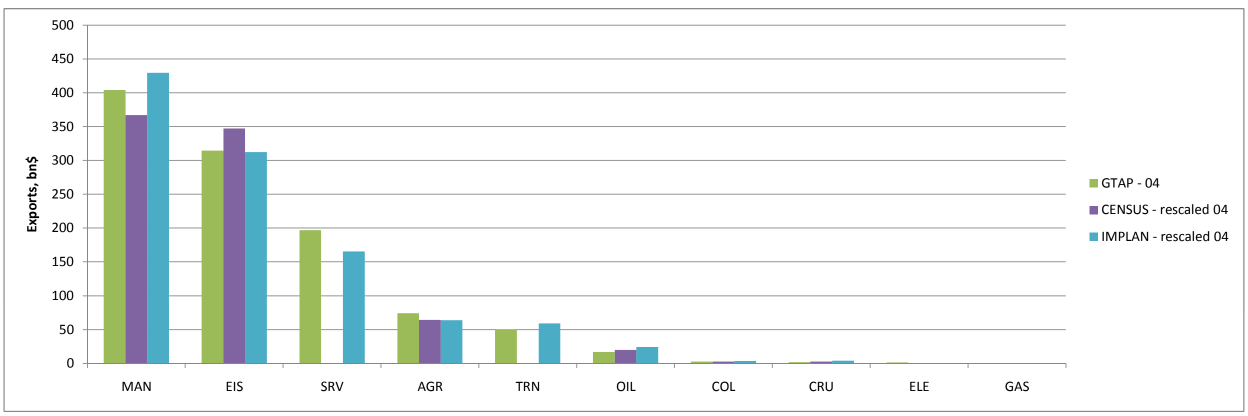

Figure 6. Exports - Deviations between data sets: 10-sector aggregation level.

5.3 Scaling

Since IMPLAN covers the whole economy as does GTAP, we can rescale the whole IMPLAN data to account for growth between 2004 and 2006. Growth in trade was quite high between 2004 and 2006: US growth in exports has been 24 %, and import growth 21 % between 2004 and 2006. GDP growth in the USA has been 3.1 % in 2004 and 4.4 % in 2005, implying a 7.6 % growth between 2004 and 2006[11].

[11] According to http://www.indexmundi.com/g/g.aspx?c=us&v=66 .

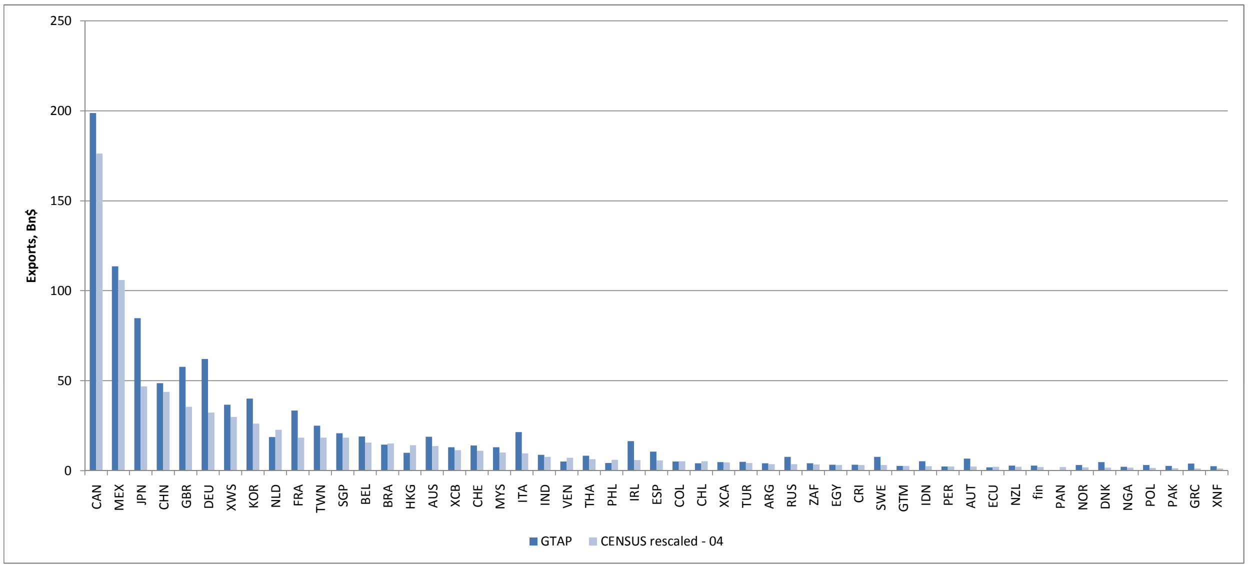

Figure 7. Exports by destination country: Deviations between data sets.

Re-scaling is not absolutely necessary as balancing would endogenously make necessary changes to IMPLAN data later on. However, pre-balance rescaling contributes to limiting the size of distortion to the IMPLAN data caused by the balancing. Here is the amount of distortion incurred, depending on the rescaling factor:

- No rescale factor—residual using 10x5 data set: 2.64e4
- Rescaling using actual GDP growth—residual using 10x5 data set: 2.35e4
- Rescaling using growth in exports implied by IMPLAN (0.93)—residual using 10x5 data set: 2.32e4
- Rescaling using growth in GDP implied by IMPLAN—residual using 10x5 data set: 2.84e4

Thus the best performance was achieved by rescaling according to export growth (rescale factor of 0.93). All economic values from IMPLAN are rescaled using this factor, except those pertaining to international trade.

5.4 Balancing

US state-level data is re-balanced such as to satisfy all the accounting identities below using a least-squares minimization of deviation with original (re-scaled) pre-balancing values. The objective to be minimized is:

$$\Omega = \sum_{X} \left[\sum_{i,rs} (X^{\star}_{i,rs} - X^{TARGET}_{i,rs})^2 \right],$$

where X include all parameters. The only exogenous constraint is that trade totals, per origin and destination country, match GTAP totals:

$$\sum_s EX_{i,s,r} = EX\_GTAPi, r$$
$$\sum_s IMi, r, s = IM\_GTAPi, r$$

Every other parameter is endogenously balanced, including per-state export and import totals. The balancing must be done for all states simultaneously in order to satisfy the domestic trade-balances. Some inter-institutional transfers are fixed. Balancing is done under the following constraints:

- **International trade constraints.** Endogenous foreign trade totals are computed. Imports are computed both as FOB and CIF (including trade costs):

$$\begin{aligned} EX_{i,s,"ftrd"} &= \sum_r EX_{i,s,r} \\ IMFOB_{i,s} &= \sum_r IM_{i,r,s} \\ IM_{i,s,"ftrd"} &= \sum_r pvxmd_{i,r,s} * IM_{i,r,s} * (1 + \sum_j vtwrratio_{j,i,r}) \,. \end{aligned}$$

  Trade revenues, by state, are calculated endogenously :

$$\begin{aligned} traderevenue_s &= \sum_{i,r} rtms_{i,r,s} * (IM_{i,r,s} * (1 - rtxs_{i,r,s} * (1 + \sum_j vtwrratio_{j,i,r}))) \\ &- \sum_{i,r} rtxs_{i,s,r} * EX_{i,s,r} \,. \end{aligned}$$

- **Domestic trade constraints.** Bilateral domestic flows, $dtrd_{i,ss,s}$, match endogenous state totals (which are calibrated to IMPLAN totals):

$$\sum_{ss} dtrd_{i,ss,s} = IM_{i,s,"dtrd"}$$
$$\sum_{ss} dtrd_{i,s,ss} = EX_{i,s,"dtrd"} \,.$$

  Domestic trade, at the national level, must be also balanced:

$$\sum_s IM_{i,s,"dtrd"} = \sum_s EX_{i,s,"dtrd"} \,.$$

- **Transfers / current account balance.** Net internal transfers $vtrn_{s,ins,t}$ over all institutions and accounts, for each state, match the state's current account balance (domestic and international). This current account balance uses FOB import flows, and includes the state's share of international net transfers, nt_s.

$$\sum_{t,ins}, vtrn_{s,ins,t} = \sum_i IMisFOB_{i,s} + IMis_{i,s,"dtrd"} - \sum_{trd} EXis_{i,s,trd} + nt_s \, .$$

The state's share of international net transfers, nt_s, is calculated endogenously under the constraint that the total matches the national amount of 43 bn$:

$$\sum_s nt_s = nt("usa") \, .$$

- **Domestic constraints.** Zero-profit conditions for sectoral production:

$$\sum_g vdfm_{i,g,s} + \sum_{trd} EXis_{i,s,trd} + vst_{i,s} =$$
$$\sum_j vdfm_{j,i,s} + \sum_{j,trd}, vifm_{j,i,s,trd} + \sum_f vfm_{f,i,s} + btax_{i,s} + \sum_{ins} evpm_{s,i,ins} \, .$$

Factor market equilibrium:

$$\sum_i vfm_{f,i,s} = \sum_{g,t} evom_{f,s,g,t} \, .$$

Budget constraint for household agents:

$$\sum_{f,t} evom_{f,s,hh,t} + vprf_{s,hh} + \sum_j evpm_{s,j,hh} + \sum_t vtrn_{s,hh,t} =$$
$$\sum_i vdfm_{i,hh,s} + \sum_{trd} vifm_{i,hh,s,trd} \, .$$

Budget constraint for government agents (trade revenues are assigned to the federal government agent):

$$\sum_{f,t} evom_{f,s,pub,t} + \sum_t btaxincome_{pub,t,s} + vprf_{s,pub}$$
$$+ \sum_j evpm_{s,j,pub} + \sum_t vtrn_{s,pub,t} + traderevenue_s =$$
$$\sum_i vdfm_{i,pub,s} + \sum_{trd} vifm_{i,pub,s,trd} \, .$$

Budget constraint for representative firms:

$$-\sum_{ins} vprf_{s,ins} + \sum_{corp} \sum_{f,t} evom_{f,s,corp,t} + \sum_j evpm_{s,j,corp} + \sum_t vtrn_{s,corp,t} =$$
$$\sum_i vdfm_{i,"i",s} + \sum_{trd} vifm_{i,"i",s,trd} \, .$$

Zero-profit conditions for both domestic and international trade:

$$\sum_g vifm_{i,g,s,\text{"}dtrd\text{"}} = IMis_{i,s,\text{"}dtrd\text{"}}$$
$$\sum_g vifm_{i,g,s,\text{"}ftrd\text{"}} = IMis_{i,s,\text{"}ftrd\text{"}} \,.$$

Output tax accounting:

$$\sum_i btax_{i,s} = \sum_{pub,t} btaxincome_{pub,t,s} \,.$$

Corporate profit accounting:

$$\sum_{pub} vprf_{s,pub} + \sum_{hh} vprf_{s,hh} = \sum_{ins} vprf_{s,ins} \,.$$

- **Sparsity.** Sparsity constraints are imposed on all variables, i.e. we fix the total number of non-zeros based on the original data set.

Exogenous deviations. **Table 14** displays deviations for each variable. Deviations are calculated as the ratio of the endogenized variable to the original IMPLAN rescaled value (1 = no change). Median deviations are all within acceptable range, but there are some extreme deviations. The last column displays the sum of absolute deviations, in bn$. The imported consumption (private and intermediate) parameter, $vifm$, requires the most adjustment. Domestic trade flows are quite affected as well. Output (vom), is relatively unaffected.

Balancing speed. Balancing needs to be done for all states at once (because of domestic trade flows), and thus is best done after the some aggregation of the sectoral and state dimensions.[12]

5.5 Other parameters

Import tariffs and export subsidies. The same national rates apply to each state. Tariff revenues are assumed to accrue to the federal government agent (FDG).

Transport costs. Transport margins are calculated such that transport costs remain proportional to calibrated trade flows. Transport service production is assigned to states according to state share of total US exports.

Intra-national trade. Deleted intra-national trade flows to same state. These where large, total internal bilateral trade goes from 2,430 to 610 (billion $). Bilateral state-to-state trade flows are also re-scaled to match state-level import and export totals from IMPLAN. This re-scaling can be quite significant (see **table 15**).

[12] Large data sets can be balanced : for example, capable of balancing a data set containing all 57 gtap sectors and 10 US regions.

Table 14. Balancing: Deviations by Parameter.

		deviation (ratio)			absolute difference			
Parameter	**Exogeneity**	**Mean**	**Median**	**Stddev**	**Mean**	**Median**	**Stddev**	**Absdev**
im(i)	exog	18.98	1.20	43.71	18.95	12.19	93.12	**552.16**
ex(i)	exog	1.29	0.91	1.06	-7.62	-1.67	20.26	**128.66**
vifm	endog	20625.43	1.21	301061.2	0.21	0.00	2.34	**1083.26**
dtrd	endog	388.05	1.09	5015.42	-0.53	-0.06	5.55	**815.53**
EXis	endog	1.26	1.01	1.13	1.95	0.08	8.14	**379.76**
IMis	endog	1.67	1.00	2.91	-1.27	-0.04	5.33	**264.83**
vdfm	endog	82.12	1.00	947.35	-0.04	-0.04	0.47	**207.02**
vtrn	endog	854.05	1.00	11349.26	-0.07	1.00	2.35	**103.99**
vom	endog	1.10	1.05	0.20	1.10	1.05	0.20	**81.67**
vfm	endog	1.00	1.00	0.12	0.09	0.00	0.35	**25.88**
IMisr	endog	2.53	1.00	14.85	0.00	0.00	0.09	**16.97**
btax	endog	1.16	1.00	0.61	0.09	-0.02	0.36	**13.03**
evom	endog	1.02	1.00	0.06	0.09	0.07	0.10	**10.07**
EXisr	endog	1.64	1.00	3.24	0.00	0.00	0.03	**7.68**
btaxincome	endog	1.36	1.01	2.10	0.10	0.09	0.11	**4.93**
vprf	endog	1.00	1.00	0.01	-0.04	-0.02	0.19	**3.20**
traderevenue	endog	1.00	1.00	0.00				

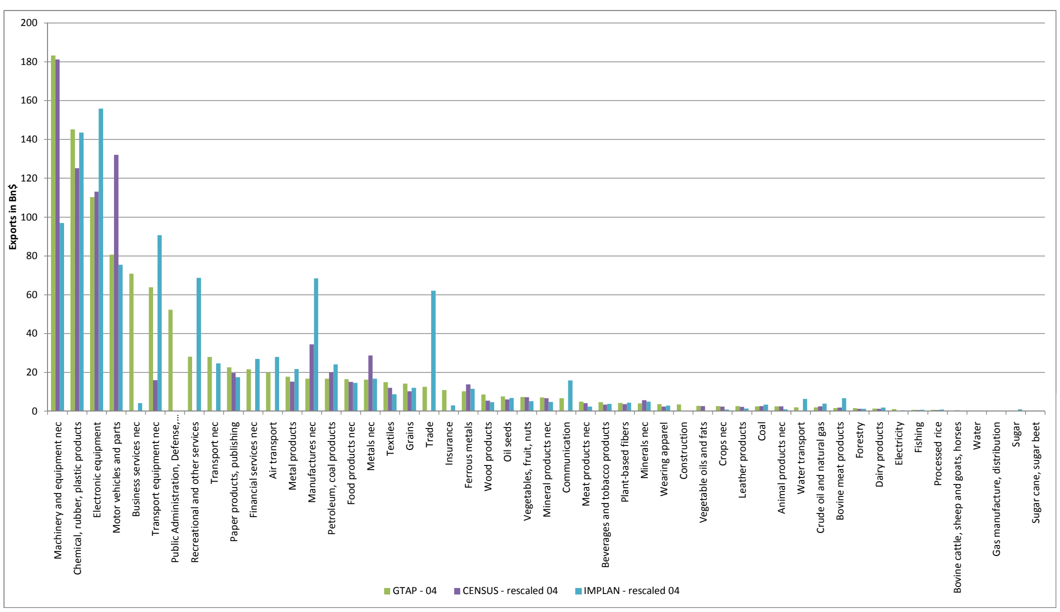

Figure 8. Exports: Deviations between data sets—GTAP aggregation level.

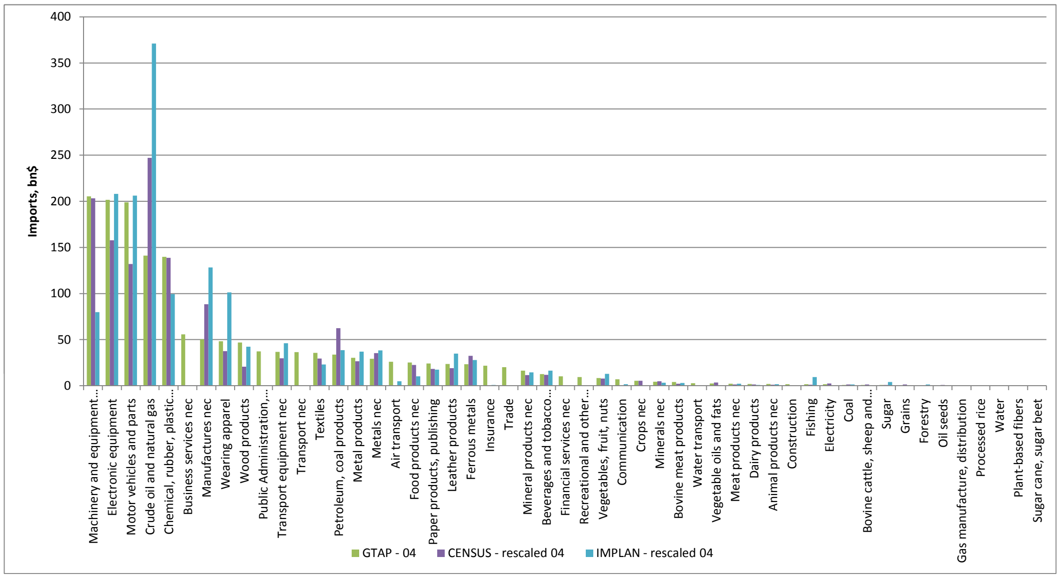

Figure 9. Imports: Deviations between data sets—GTAP aggregation level.

Table 15. Intra-national Trade Flows Rescaling.

	Median	Mean	Stdev
Exports	4.91	23.90	43.85
Imports	5.05	25.34	49.12

Transfers. IMPLAN data contains extensive data about inter-institutional transfers. Each state's net transfers equals it's trade balance. Some of the accounts in the transfer data are balanced within the state: nint, gint, pitx, fees, pmvt, pptx, fish. These are constrained to remain unchanged in the calibration procedure.

Production factors. GTAP data includes 5 factors of production. IMPLAN data only contains labor and capital. Here is how GTAP factors where aggregated to match these:

- Capital = Capital + land + natural resources
- Labor = skilled labor + unskilled labor

Factor reward attribution - EVOM. In GTAP, only one representative consumer agent receives all factor rewards. In IMPLAN this data is not only disaggregated to the different households but includes rewards attributed to government agents and enterprises. As can be seen in **Table 16**, the federal government agent (FDG) is endowed with quite a bit of labor, and the enterprises are endowed with most of the capital. Capital and labor endowments of enterprises is assigned to households according to their share of labor endowments. Capital payments to government agents are assigned to households according to their share of capital endowments. **Table 16** gives an overview of values in the $evom$ parameter.

Table 16. Factor rewards in EVOM.

	Capital	Labor	Assigned to
Enterprises	3190.9	9.1	Households
Low-income hh	442.9	1747.6	Households
High-income hh	1214.7	4786.3	Households
Federal gov.	45.6	869.4	Labor to gov, capital to households
State govs.	0.5	25.8	Labor to gov, capital to households

Current account balance. The current account balance (VB) consists of the trade balance (TB) and other transfers (NT):

$$vb(r) = nt(r) + tb(r) \, .$$

Table 17. Current Account Decomposition.

Parameter	Value (bn$)
USA current account deficit (GTAP)	568.006
USA trade deficit (GTAP)	527.911
USA other transfers deficit (GTAP)	40.095
USA trade deficit (IMPLAN - rescaled)	574.891
USA trade deficit (IMPLAN)	612.32

The sum of each state's trade balance vis-a-vis international trading partners is constrained to match the GTAP total. The sum of internal transfers in each state matches the state's trade balance (intra- and international) in the IMPLAN data. The transfers explicitly included in IMPLAN do not allow to identify which elements of the transfers come from outside the state (national or international). In order to balance the internal transfers in the calibration procedure, they are assumed to match a state-level current account balance condition.

Thus, this includes the other net transfers (NT), which are freely attributed to each state under the only constraint of adding up to the US total net transfer deficit (40.095 bn$). It is also impossible to distinguish which part of the transfers accrue to government agents or to households.

Investment (VINVH). Investment demand is attributed to households based on their share of capital income.

Stock changes / institutional make (EVPM). Stock changes and institutional make and exports are fairly small relative to production. The stock changes (negative) are imputed to sectoral production. Zero-profit condition is held by adjusting factor inputs and endowments accordingly.

5.6 Tax rates

The tax rates and revenues are allowed to vary in calibration procedure.

Output tax (RTO). Output tax rates are calculate using ”btax” (indirect Business tax). Tax revenue accrues to different government agents according to IMPLAN values found in $EVOM$.

Labor taxes (RTF(”lab”)). Are calculated based on FICA tax rates. Using the ”sstw” and ”sstf” accounts in evom.

Capital income tax (RTF(”cap”)). Are calculated based on the ”ctax” account in inter-institutional transfers. Capital tax payments are distributed to household based on share of capital payments. All tax revenue is assumed to accrue to FDG.

Average personal income tax (only in IMPLAN, not in GTAP): pitx(h,s). Is calculated from the ”ptax” account in inter-institutional transfers.

6. DETAILED MODEL FORMULATION

This section describes the model used in “Leakage from sub-national climate initiatives: The case of California” by Justin Caron, Sebastian Rausch, Niven Winchester
The computable general equilibrium model is formulated as a system of nonlinear inequalities. We represent an economic equilibrium through two classes of conditions: zero profit and market clearance. The former class determines activity levels (z) and the latter determines price levels (p). In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition. Following Mathiesen (1985) and Rutherford (1995), we formulate the model as mixed complementarity problem.

A complementary-based approach has been shown to be convenient, robust, and efficient (Mathiesen, 1985; Rutherford, 1995). A characteristic of many economic models is that they can be cast as a complementary problem, i.e. given a function F: $R^n \longrightarrow R^n$, find $z \in R^n$ such that $F(z) \geq 0$, $z \geq 0$, and $z^T F(z) = 0$. The complementarity format embodies weak inequalities and complementary slackness, relevant features for models that contain bounds on specific variables, e.g. activity levels which cannot a priori be assumed to operate at positive intensity. Numerically, we solve the model in GAMS using the PATH solver (Dirkse and Ferris, 1995).

Variables, parameters, and set notation used in the algebraic exposition of the model below are summarized in **Tables** A1-A3. The nested structures of CES functions used to describe production and consumption technologies are shown in **Figures A 1-A 6** in this appendix.

Zero profits. Let $\Pi_{ir}^{Y}(p)$ denote the unit profit function of industry i in region r which is calculated as the difference between unit revenue (R_{ir}) and unit costs (C_{ir}) where:

$$C_{ir}(p) = \mathit{min}\{p_{ir}^{l} L_{ir} + p_{ir}^{k} K_{ir} + p_{ir}^{z} R_{zir} + \sum_{j} p_{jir} X_{jir} \mid F_{ir}(L_{ir}, K_{ir}, R_{ir}; X_{1ir}, \ldots, X_{Iir}) = 1\} \tag{19}$$

where $F_{ir}(\cdot)$ is given by Eq. (1), and

$$R_{ir}(p) = \mathit{max}\{p_{ir}^{Y} Y_{ir} \mid Y_{ir} = 1\}\,. \tag{20}$$

Zero profits implies that no production activity makes positive profits, i.e.:

$$-\Pi_{ir}^{Y}(p) = C_{ir}^{Y} - R_{ir}^{Y} \geq 0 \qquad \perp \qquad Y_{ir}\,. \tag{21}$$

Similar conditions hold for the aggregation of domestically produced variety and imported variety for good i for each demand class (i.e., intermediate, investment, private, and government demand analogous to equations (4), (5), (6), and (7)):

$$-\Pi_{ir}^{X}(p) = C_{ir}^{X} - R_{ir}^{X} \geq 0 \qquad \perp \qquad X_{ir} \tag{22}$$

$$-\Pi_{ir}^{C}(p) = C_{ir}^{C} - R_{ir}^{C} \geq 0 \qquad \perp \qquad C_{ir} \tag{23}$$

$$-\Pi_{ir}^{I}(p) = C_{ir}^{I} - R_{ir}^{I} \geq 0 \qquad \perp \qquad I_{ir} \tag{24}$$

$$-\Pi_{ir}^{G}(p) = C_{ir}^{G} - R_{ir}^{G} \geq 0 \qquad \perp \qquad G_{ir}\,. \tag{25}$$

The level of the imported variety of good i (M_{ir}) is determined in equilibrium by the following zero-profit condition (based on Eq. (8)):

$$-\Pi_{ir}^{M}(p) = C_{ir}^{M} - R_{ir}^{M} \geq 0 \qquad \perp \qquad M_{ir} \tag{26}$$

and the level of the domestic variety of good i (D_{ir}) is complementary to (based on Eq. (9)):

$$-\Pi_{ir}^{D}(p) = C_{ir}^{D} - R_{ir}^{D} \geq 0 \qquad \perp \qquad D_{ir}\,. \tag{27}$$

Finally, zero-profits for aggregating government goods requires that:

$$-\Pi_r^G(p) = C_r^G - R_r^G \geq 0 \qquad \perp \qquad G_r\,. \tag{28}$$

The zero-profit condition for "producing" one unit of utility (based on the utility function in (3)) is given by

$$-\Pi_r^U(p) = C_r^U - R_r^U \geq 0 \qquad \perp \qquad U_r \tag{29}$$

where the unit expenditure function is given by

$$C_r^U(p, M) = \mathit{min}\{p_r^i I_r + p_r^l N + \sum_i p_{ir}^c C_{ir} \leq p_r^k \overline{K}_r + \sum_i p_{ir}^{VK} \overline{\boldsymbol{VK}}_{ir} + p_{fr}^R \overline{R}_{fr} + p_r^l \overline{L}_r + T_r \mid U_r(\cdot) = 1\}\,. \tag{30}$$

Market clearance. The second class of equilibrium conditions is that at equilibrium prices and activity levels, the supply of any commodity must balance or exceed demand.[13]

Market clearance for the domestically produced variety of good i by US region s involves summing up intermediate and final (private, investment, and government) demands:

$$Y_{is} \geq \underbrace{D_{is}\frac{\partial \Pi_{is}^D}{\partial p_{is}^Y}}_{\text{local demand}} + \underbrace{\sum_{s' \neq s} D_{is'}\frac{\partial \Pi_{is'}^D}{\partial p_{is}^Y}}_{\text{demand by US regions}} + \underbrace{\sum_t M_{it}\frac{\partial \Pi_{it}^M}{\partial p_{is}^Y}}_{\text{demand by international regions}} \qquad \perp \qquad p_{is}^Y\,, \tag{31}$$

and for variety of good i produced by an international region t is given by:

$$Y_{it} \geq \underbrace{D_{it}\frac{\partial \Pi_{it}^D}{\partial p_{it}^Y}}_{\text{domestic demand}} + \underbrace{\sum_s D_{is}\frac{\partial \Pi_{is}^D}{\partial p_{it}^Y}}_{\text{demand by US regions}} + \underbrace{\sum_{t' \neq t} M_{it'}\frac{\partial \Pi_{it'}^M}{\partial p_{it}^Y}}_{\text{demand by international regions}} \qquad \perp \qquad p_{it}^Y\,. \tag{32}$$

The market for domestically produced variety of good i for a US region or international region r is balanced if:

$$D_{ir} \geq X_{ir}\frac{\partial \Pi_{ir}^X}{\partial p_{ir}^D} + C_{ir}\frac{\partial \Pi_{ir}^C}{\partial p_{ir}^D} + I_{ir}\frac{\partial \Pi_{ir}^I}{\partial p_{ir}^D} + G_{ir}\frac{\partial \Pi_{ir}^G}{\partial p_{ir}^D} \qquad \perp \qquad p_{ir}^D\,, \tag{33}$$

and the market for imported variety of good i by a US region or international region r is balanced if:

$$M_{ir} \geq X_{ir}\frac{\partial \Pi_{ir}^X}{\partial p_{ir}^M} + C_{ir}\frac{\partial \Pi_{ir}^C}{\partial p_{ir}^M} + I_{ir}\frac{\partial \Pi_{ir}^I}{\partial p_{ir}^M} + G_{ir}\frac{\partial \Pi_{ir}^G}{\partial p_{ir}^M} \qquad \perp \qquad p_{ir}^M\,. \tag{34}$$

[13] Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's Lemma or the Envelope Theorem), which appear subsequently in the market clearance conditions.

Market clearance condition for inter-industry (intermediate) output i in region r is given by:

$$X_{ir} \geq \sum_j Y_{jr} \frac{\partial \Pi^Y_{jr}}{\partial p^X_{ir}} \qquad \perp \qquad p^X_{ir}\,. \tag{35}$$

Market clearance conditions for final consumption goods are given by:

$$C_{ir} \geq U_r \frac{\partial \Pi^U_r}{\partial p^C_{ir}} \qquad \perp \qquad p^C_{ir}\,. \tag{36}$$

Market clearance conditions for investment goods are given by:

$$I_{ir} \geq U_r \frac{\partial \Pi^U_r}{\partial p^I_{ir}} \qquad \perp \qquad p^I_{ir}\,. \tag{37}$$

Market clearance conditions for government goods are given by:

$$G_{ir} \geq G_r \frac{\partial \Pi^G_r}{\partial p^G_{ir}} \qquad \perp \qquad p^G_{ir}\,. \tag{38}$$

Market clearance for the composite government good is:

$$G_r = \qquad \left(TAX_r - \sum_r T_r - B_r \right) / p^G_r \perp \qquad p^G_r\,. \tag{39}$$

Regional labor markets are in equilibrium if:

$$\overline{L}_r - N_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^l_r} \qquad \perp \qquad p^l_r\,. \tag{40}$$

Capital markets for international region r are balanced if:

$$\overline{K}_t \geq \sum_i Y_{it} \frac{\partial \Pi^Y_{it}}{\partial p^k_t} \qquad \perp \qquad p^k_t\,. \tag{41}$$

Integrated capital markets for US regions are balanced if:

$$\sum_s \overline{K}_s \geq \sum_s \sum_i Y_{is} \frac{\partial \Pi^Y_{is}}{\partial p^k} \qquad \perp \qquad p^k\,. \tag{42}$$

Sector-specific vintage capital markets clear if:

$$\overline{VK}_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{VK}_{ir}} \qquad \perp \qquad p^{VK}_{ir}\,. \tag{43}$$

Resource markets for region r are balanced if:

$$\overline{R}_{fr} \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^R_{fr}} \qquad \perp \qquad p^R_{fr}\,. \tag{44}$$

By Walras' Law, we can omit the market for leisure.

Table 18. Indices and sets.

i,j	Sectors and goods
s	US regions
t	International regions
r	All regions
fr	Fossil resources

Table 19. Activity levels and prices.

Activity levels	
Y_{ir}	Production of variety of good i in region r
X_{ir}	Inter-industry intermediate demand for variety of good i in region r
C_{ir}	Private demand for good i in region r
I_{ir}	Investment demand for variety of good i in region r
G_{ir}	Government demand for variety of good i in region r
M_{ir}	Total imports for good i in region r
D_{ir}	Total domestic demand for variety of good i in region r
G_r	Total government demand in region r
U_r	Private utility
Prices	
p_{ir}^{Y}	Price of variety of good i in region r
p_{ir}^{D}	Price of domestic composite of good i in region r
p_{ir}^{M}	Price of imported composite of good i in region r
p_{ir}^{X}	Price of inter-industry (intermediate) output of good i in region r
p_{ir}^{C}	Price of good i for private demand in region r
p_{ir}^{I}	Price of good i for investment demand in region r
p_{ir}^{G}	Price of good i for government demand in region r
p_{r}^{G}	Price of composite government demand in region r
p_{r}^{l}	Wage rate in region r
p_{s}^{k}	Capital rental rate in international region t
p^{k}	Capital rental rate in the US
p_{ir}^{VK}	Price of vintage capital in sector i in region r
p_{fr}^{R}	Price of fossil fuel *fr* in region r

Table 20. Endowments and exogenous flows.

$\overline{K}_r$	Capital endowment for region r
$\overline{VK}_{ir}$	Vintage capital endowment for sector i in region r
$\overline{L}_r$	Time endowment of region r
$\overline{R}_{fr}$	Resource endowment of type *fr*
T_r	Transfer payments to households in region r
TAX_r	Tax revenue for government in region r
B_r	Initial balance of payments surplus or deficit in region r (Note that $\sum_r B_r = 0$)

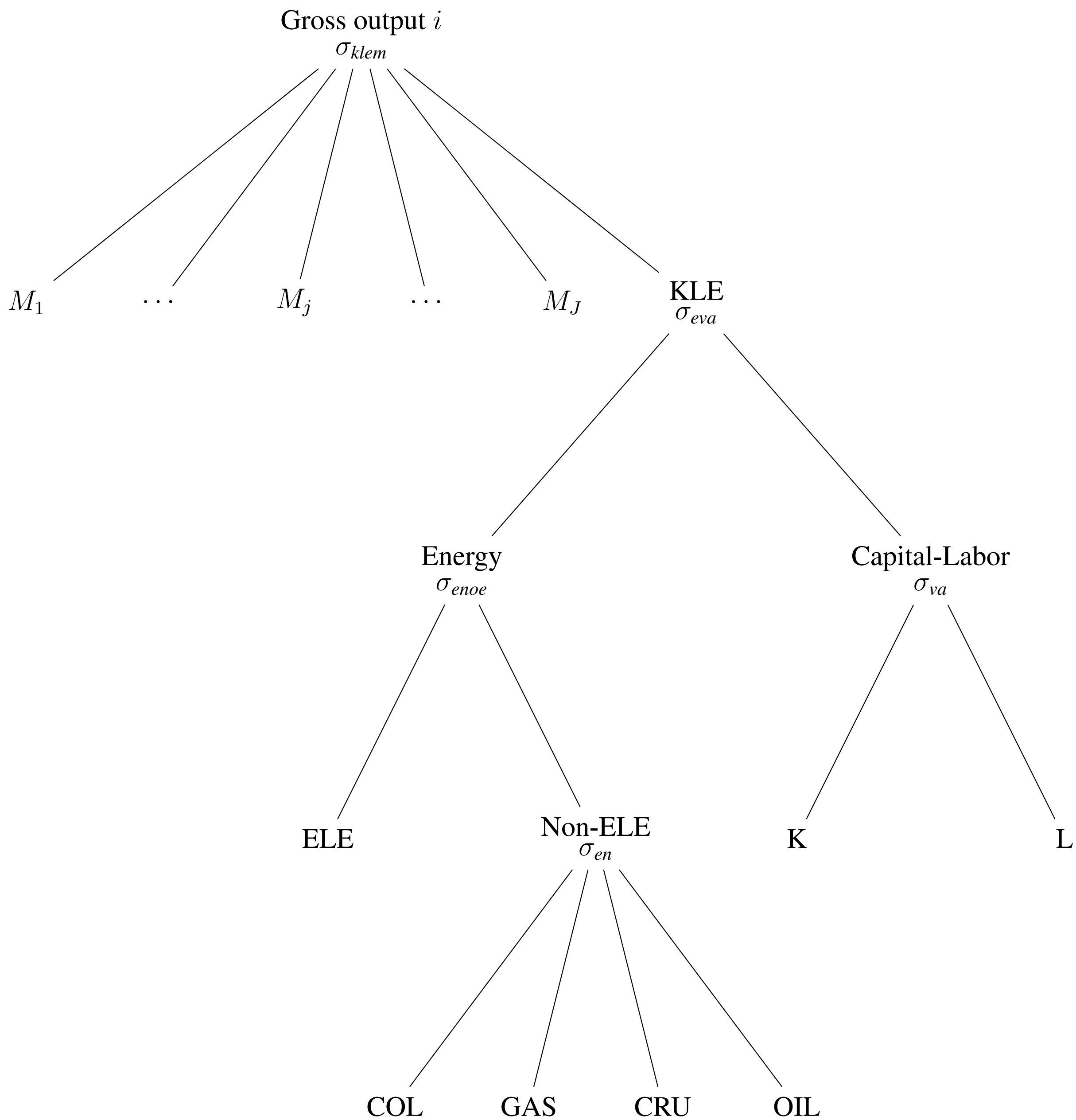

Figure A 1. Structure of production for $i \in \{$TRN,EIS,SRV,CRP,I_S,NFM,NMM,PPP,MAN$\}$.

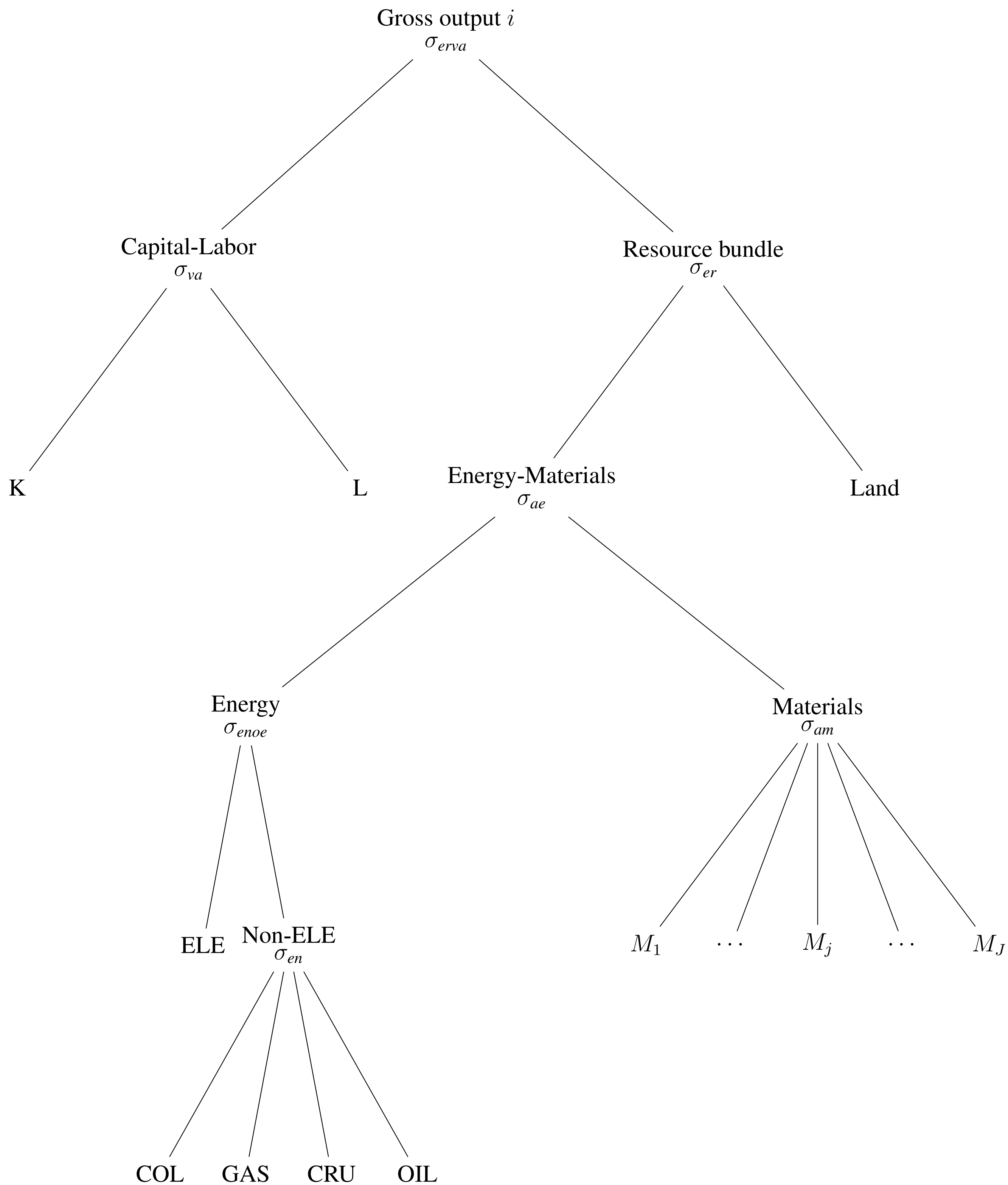

Figure A 2. Structure of production for $i \in \{\text{AGR}\}$.

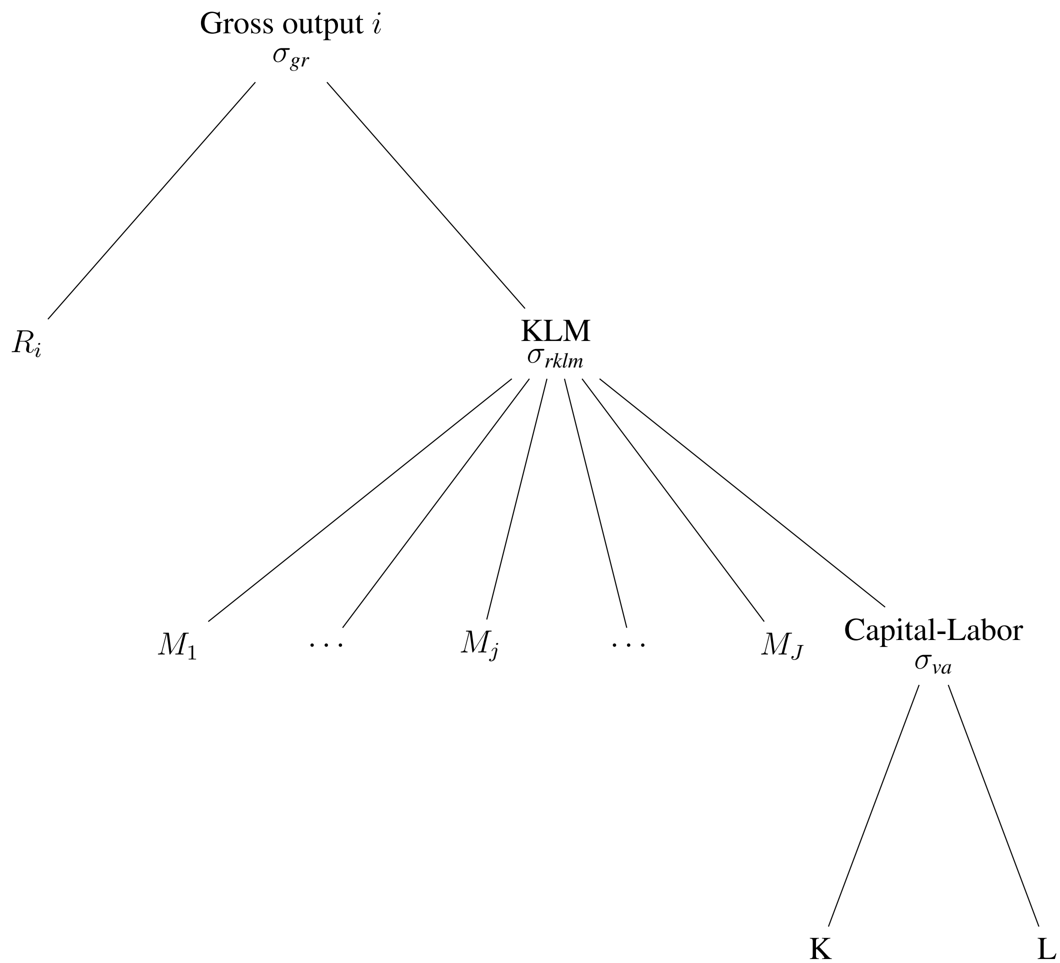

Figure A 3. Structure of primary energy sectors $i \in \{$COL,CRU,GAS$\}$.

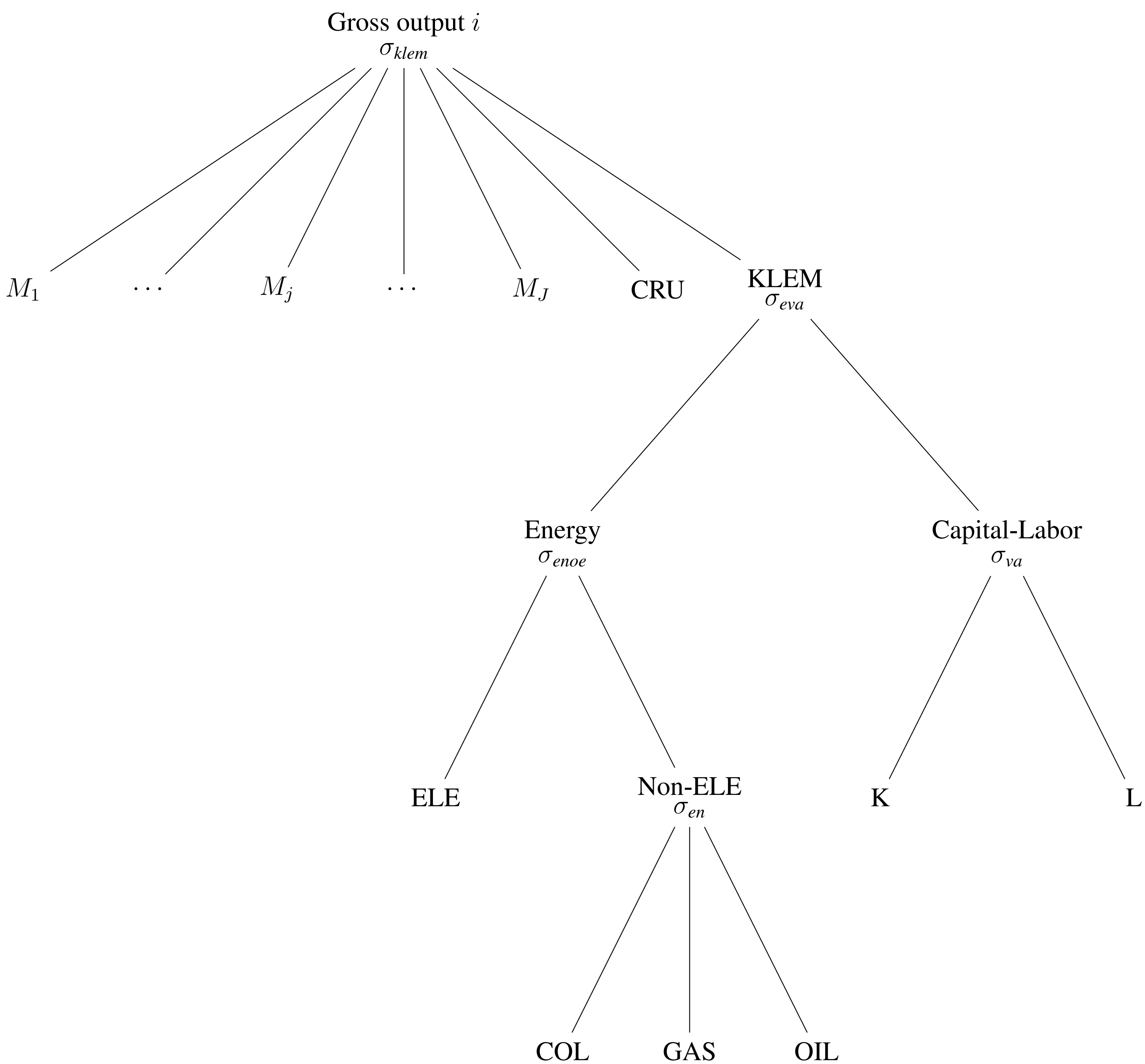

Figure A 4. Structure of production for $i \in \{\text{OIL}\}$.

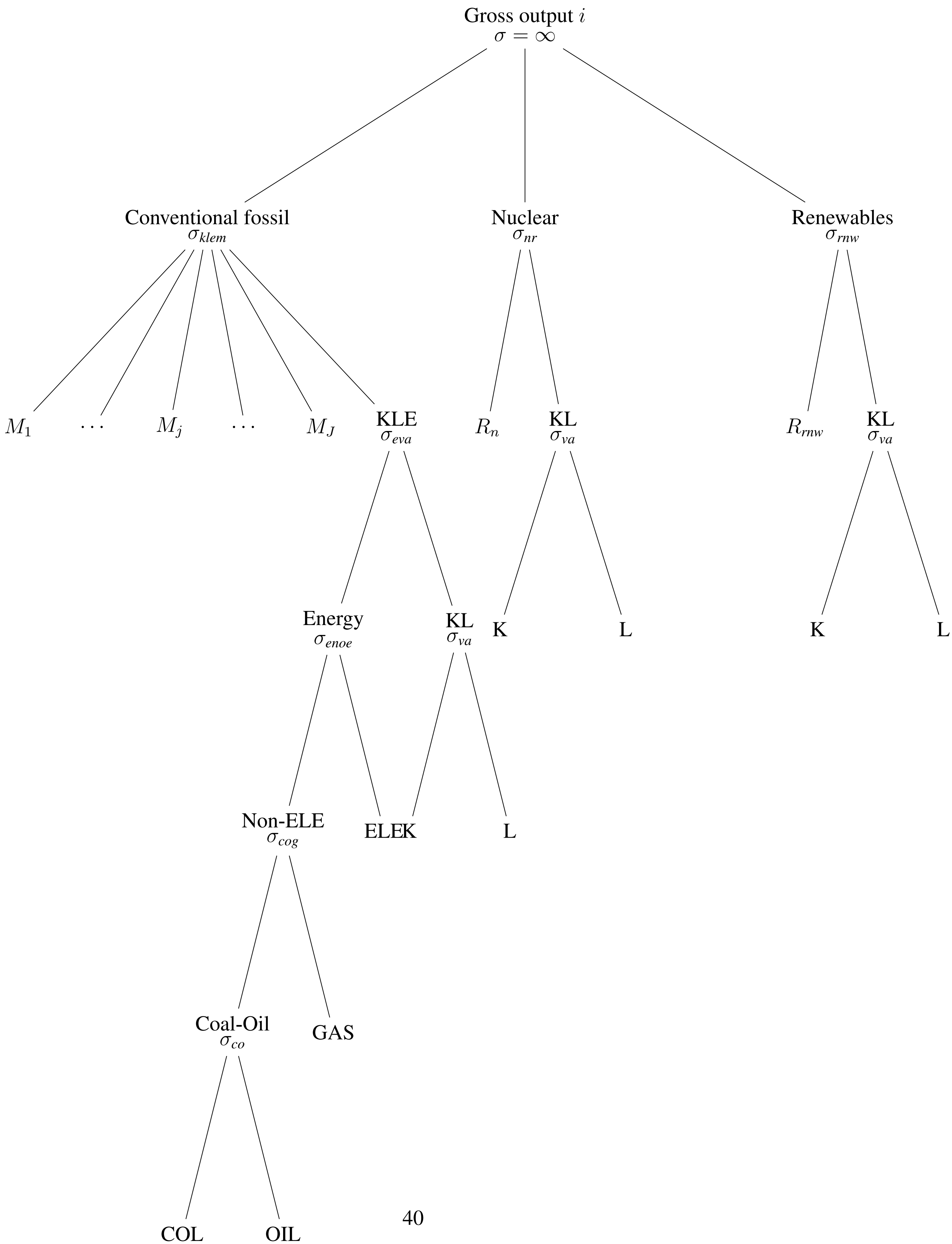

Figure A 5. Structure of electricity production $i \in \{\text{ELE}\}$.

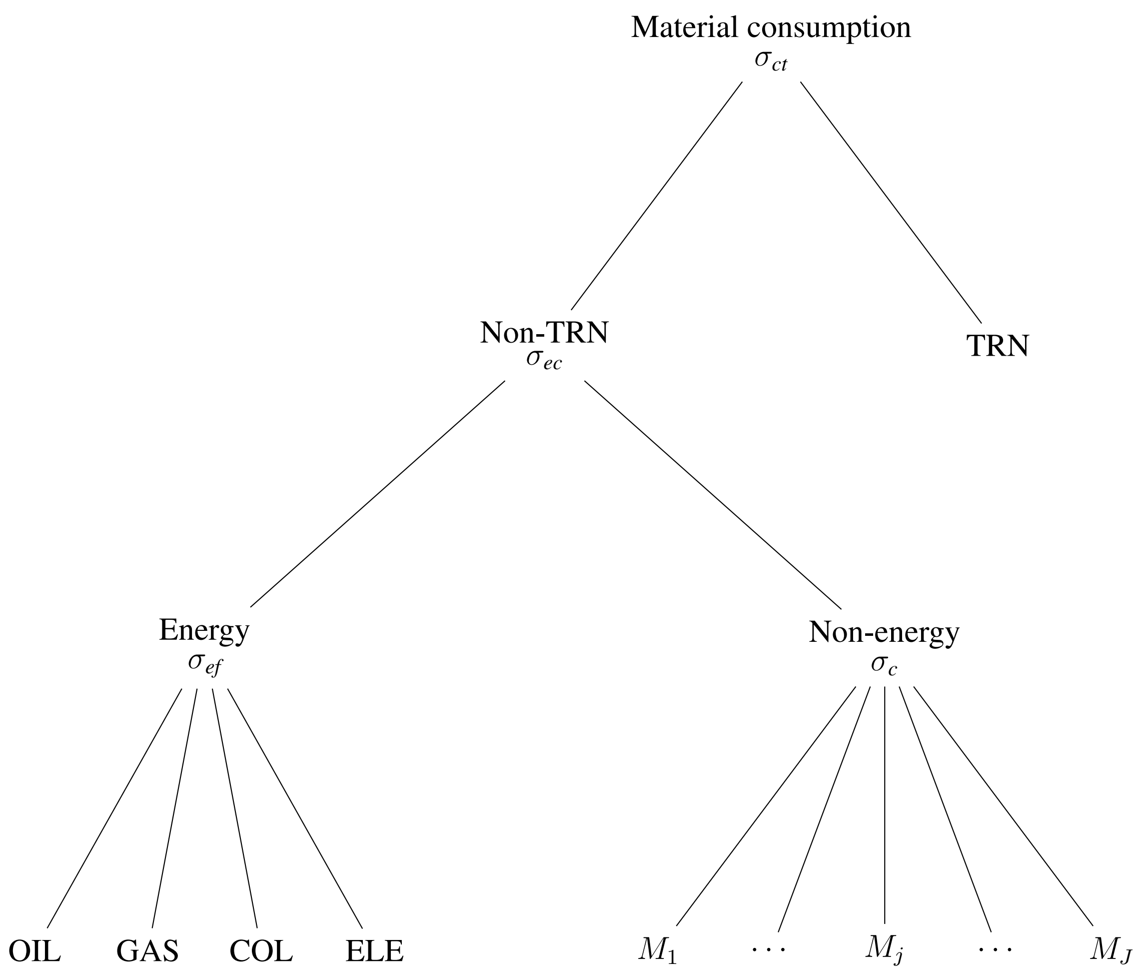

Figure A 6. Structure of private material consumption.

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