Leakage from Sub-national Climate Initiatives: The Case of California

Justin Caron, Sebastian Rausch and Niven Winchester

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Abstract

With federal policies to curb greenhouse gas emissions in the U.S. stagnating, California has taken action on its own. We estimate the impact of California's cap-and-trade program on the leakage of emissions to other regions using a calibrated general equilibrium model. Sub-national policies can lead to high leakage rates as state economies are generally closely connected to other economies, including integration of electricity markets. Measures that will prevent leakage from California's cap-and-trade program include requiring permits to be surrendered for emissions embodied in imported electricity and legislation banning "resource shuffling". Under a cap-and-trade policy without measures to reduce leakage, the price of emission permits is $12 per ton of CO_2 *and emissions in other regions increase by 46% of the reduction in emissions in California. When imported electricity is included in the program and resource shuffling is banned, the carbon price is $65, there is negative leakage to regions exporting electricity to California, positive leakage to other regions and the overall leakage rate is 2%. We conclude that although there is potential for large increases in emissions elsewhere due to California's cap-and-trade policy, enforcement of requirements for imported electricity will be effective at curtailing leakage.*

Contents

1. INTRODUCTION

Leakage occurs when greenhouse gas (GHG) restrictions in some regions increase emissions in unconstrained regions. Climate policies can cause leakage via their impacts on trade, fossil fuel

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prices and factor movements. Leakage via the trade channel occurs when relative price changes induce substitution away from production in carbon-constrained regions and towards imports from unconstrained regions. The fossil fuel price channel is generally thought to increase emissions in unconstrained regions, as climate policies reduce fossil fuel prices and increase energy consumption in these regions. However, as noted by Burniaux (2001), if the supply of coal is more elastic than the supply of less carbon-intensive fuels, climate policies may reduce emissions in unconstrained regions (i.e., result in negative leakage). Negative leakage can also arise if energy efficiency improvements induced by the policy cause factor migration from unconstrained regions to constrained regions (Fullerton *et al.*, 2011).

The mechanisms behind leakage from national climate policies have been thoroughly investigated in the existing literature. The case of sub-national policies, however, is different in that both factor and traded good markets are more integrated at the national level than at the international level. Indeed, numerous gravity-based empirical exercises have found national borders to inhibit trade. The first estimates of a "border effect" in McCallum (1995) have been revised by Anderson and van Wincoop (2003), who find trade between U.S. states to be 2.24 times larger than trade between states and Canadian provinces. Factor markets are also more tightly integrated within national borders than across them. Using Canadian data, Helliwell and McKitrick (1999) find that the national border clearly reduces capital flows, whereas such resistance is not found for intra-national borders (between provinces).

With federal initiatives to curb GHGs stalling in the U.S., sub-national polices have received greater focus. To date, two regional cap-and-trade policies have been legislated in the U.S. First, 10 states in the northeast are members of the Regional Greenhouse Gas Initiative (RGGI). The program, which began on January 1, 2009, sets state-level caps on electricity emissions and allows trading of emission permits among states. Second, a cap-and-trade program on emissions from electricity generation and certain industries will operate in California beginning in 2013. Transport and other fuels will be included in this program from 2015, by which time the cap will cover an estimated 85% of California's GHG emissions sources. In addition to restricting emissions from in-state production, the policy requires permits to be surrendered for emissions embodied in imported electricity. At the time of writing, California's policy is the only economy-wide cap-and-trade program to be enacted in the U.S. and is set to become the second largest carbon market behind the EU Emissions Trading Scheme (ETS).

In this paper, we use a calibrated general equilibrium model to examine the leakage implications of sub-national climate policies using California's cap-and-trade program as an example. Moreover, legislation in both California and the EU allow for their programs to be linked with other systems and we accordingly investigate the effects of allowing trading of permits between California and the EU.

General equilibrium assessments of leakage from federal policies commonly estimate leakage rates between 10% and 30% (see, for example, Felder and Rutherford, 1993; Babiker, 2005; Babiker and Rutherford, 2005; Bernstein *et al.*, 1999; and Copeland and Taylor, 2005). Relatively few studies have focused on leakage from sub-national initiatives. One exception is Sue Wing and

Kolodziej (2008), who consider the RGGI using a multi-state computable general equilibrium (CGE) model of the U.S. economy. The authors estimate that 49-57% of emissions abated by RGGI electricity generators will be offset by unconstrained sources. A shortcoming in the framework employed by Sue Wing and Kolodziej (2008) is that states source intra-national imports from a national pool of state exports. As a result, the share of, say, state i's exports in j's imports is the same for all j. This assumption can bias results if emissions intensities and/or imports shares differ across states. Additionally, as the authors do not track trade flows between each state and the rest of the world, their framework is unable to consider leakage to international sources.

Our point of difference is a computable general equilibrium model calibrated to a dataset which includes 15 U.S. states or aggregated regions and 15 countries or regions in the rest of the world. The model tracks bilateral trade among all regions, including trade among U.S. regions and trade between U.S. regions and international regions. Due to its detailed treatment of trade flows, our model is ideally suited to examining leakage from sub-national climate initiatives.

This paper has four further sections. The next section provides an overview of California's cap-and-trade program. Our modeling framework is outlined in Section 3. Section 4 outlines our scenarios, discusses results and reports findings from a sensitivity analysis. Section 5 concludes.

2. CALIFORNIA'S CAP-AND-TRADE PROGRAM

California's Global Warming Solutions Act of 2006, Assembly Bill 32, was signed into law on September 27, 2006. The bill required the California Air Resources Board (CARB) to develop regulations and market-based measures to reduce California's GHG emissions to 1990 levels by 2020. The primary emissions reduction tool in the bill is a cap-and-trade program for GHG emissions. On October 20, 2011, the CARB finalized details of the cap-and-trade program and filed the legislation with the California Office of Administrative Law. The legislations was approved by this office on December 13, 2011.

Emissions covered by the program include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), nitrogen trifluoride (NF_3), and other fluorinated greenhouse gases. The first phase of compliance for the program begins on January 1, 2013. Covered entities in the first phase include electric utilities, electricity importers, and industrial facilities that emit 25,000 metric tons or more of carbon dioxide equivalent (CO_2e) annually. Industrial sources covered by the policy include petroleum refiners, producers of cement, iron, steel, glass and lime, and pulp and paper manufacturing.

Requiring allowances to be turned in for the emissions embodied in imported electricity is similar to imposing an electricity tariff. According to the legislation, emissions embodied in imported electricity are calculated as the sum of emissions from "specified" and "unspecified" sources, with adjustments for electricity from eligible renewable sources, electricity that is imported and exported during the same hour, and electricity from regions with a cap-and-trade policy linked to California. A specified source is a particular generating unit or facility for which electricity generation can be confidently tracked. As a component of embodied emissions are traced back to emissions from individual generating units, a deliverer of electricity to California's grid could reduce its CO_2 liability by sourcing low-emissions electricity from a new source and diverting high-emissions sources previously sent to California to other states. However, such actions may be prevented by regulations that prohibit "resource shuffling", which is defined as "any plan, scheme, or artifice to receive credit based on emissions reductions that have not occurred, involving the delivery of electricity to the California grid" (CARB, 2011, p. 38). As enforcing the bill's resource shuffling regulations may require California to sanction importers based on actions by out of state third parties, the resource shuffling legislation raises several legal issues (Linklaters, 2011).

The second phase of compliance will commence on January 1, 2015 and will expand the set of covered entities to include transportation fuels, natural gas and other fuels. An estimated 85% of California's emissions sources will be covered in the second phase. Initially, most allowances will be allocated for free. The distribution of allowances to electricity providers will be based on historical emissions and sales. Allowances allocated to industrial facilities will use a formula based on output. The allocation of free allowances will decrease and a larger share will be auctioned over time.

Approved offset credits may be used to cover up to 8% of emissions permitted under the cap. Offset credits may be sourced from certified offset programs in the U.S., Canada and Mexico; approved early action offset schemes; and authorized sector-based crediting programs in eligible jurisdictions. Under current legislation, offsets could account for up to 85% of the reduction in emissions. However, economic analysis by the CARB indicates that, under reasonable assumptions, offsets will account for a maximum of 49% of emissions reductions and, due to tight eligibility restrictions, offset usage may be much less (Mulker, 2011). Another cost containment measure is a price ceiling on emissions permits, which is \$40 in 2013 and rises by 5% percent plus the rate of inflation per year.

CARB (2011, Subarticle 12, p. A-153) also sets out conditions for linking California's program to other trading schemes. Once an external ETS has been approved by the CARB, compliance instruments issued by other programs may be used to meet California's requirements. In this connection, California has pursued a regional approach to climate policy as a member of the Western Climate Initiative (WCI). The initiative was launched in February 2007 (original with five member states) with a goal of reducing region-wide emissions by 15% from 2005 levels by 2020. Current partners include the U.S. states of Arizona, California, Montana, New Mexico, Oregon, Utah and Washington and the Canadian provinces of British Columbia, Manitoba, Ontario and Quebec.[1] The agreement requires each member to implement its own cap-and-trade system and participate in a cross-border GHG registry. The first phase of the regional cap-and-trade program was due to begin on January 1, 2012. However, although California's authorities have been in close contact with staff in some Canadian provinces, California is the

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[1] Several regions are members of the WCI as observers. Observers include the U.S. states of Alaska, Colorado, Idaho, Kansas, Nevada and Wyoming; the Canadian province of Saskatchewan; and the Mexican states of Baja California, Chihuahua, Coahuila, Nuevo Leon, Sonora and Tamaulipas.

Table 1. Data sources.

Data and parameters	Source
Social accounting matrices, bilateral trade	
international regions	Global Trade Analysis Project (GTAP, 2008), Version 7
U.S. states	IMPLAN (2008) and gravity model (Lindall *et al.*, 2006)
U.S. state-to-country bilateral trade flows	Origin of Movement (OM) and State of Destination (SD), U.S. Census Bureau (2010)
Physical energy flows and energy prices	
international regions	Global Trade Analysis Project (2008)
U.S. states	State Energy Data System (SEDS), EIA (2009)
Trade elasticities	Global Trade Analysis Project (2008) and own calibration
Energy demand and supply elasticities	Paltsev *et al.* (2005)

only partner that has set out mechanisms for capping emissions at the time of writing. Progress towards cap-and-trade legislation in other states and provinces has been hindered by the recession and political opposition. Notably, on February 2, 2010, Governor Brewer signed an executive order stating that Arizona would not endorse a cap-and-trade program.

Elsewhere, a cap-and-trade program has operated in the EU since 2005. Details of the EU-ETS are set out in Directive 2003/87/EC (European Union, 2003). This legislation allowed the EU-ETS to be linked to regims in other industrialized countries that ratified the Kyoto Protocol. In 2009, the European Commission amended the EU-ETS under Directive 2009/29/EC. One amendment expanded the scope of EU climate policy to allow trading of emissions permits between the EU-ETS and sub-national programs. Specifically, amendment 27 of Article 1 added the following paragraph to Article 25 of Directive 2003/87/EC: “Agreements may be made to provide for the recognition of allowances between the [European] Community scheme and compatible mandatory greenhouse gas emissions trading systems with absolute emissions caps established in any other country or in sub-federal or regional entities” (European Union, 2009, p. 81).

3. MODELING FRAMEWORK

3.1 Data

This study makes use of a comprehensive energy-economy dataset that features a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade for the year 2004. The dataset merges detailed state-level data for the U.S. with national economic and energy data for regions in the rest of the world and is outlined in detail by Caron and Rausch (2011). Social accounting matrices (SAMs) in our hybrid dataset are based on data from the Global Trade Analysis Project (Global Trade Analysis Project, 2008), IMPLAN (IMpact analysis for PLANning) data (IMPLAN, 2008), and U.S. state-level accounts on energy balances and prices from the Energy Information Administration (2009). **Table 1** provides an overview of data sources.

The GTAP dataset provides consistent global accounts of production, consumption, and bilateral trade as well as consistent accounts of physical energy flows and energy prices. Version 7 of the database, which is benchmarked to 2004, identifies 113 countries and regions and 57 commodities. The IMPLAN data specifies benchmark economic accounts for the 50 U.S. states (and the District of Columbia). The dataset includes input-output tables for each state and identifies 509 commodities as well as existing taxes. The base year for the IMPLAN accounts in the version we use here is 2006. To improve the characterization of energy markets in the IMPLAN data, we use least-square optimization techniques to merge IMPLAN data with data on physical energy quantities and energy prices from the Department of Energy's State Energy Data System (SEDS) for 2006 (Energy Information Administration, 2009).[2]

Data describing trade between regions outside of the U.S. are taken from GTAP and reflect bilateral flows from the United Nations Commodity Trade Statistics Database. Bilateral state-to-state trade data in the IMPLAN database are derived using a gravity approach described in Lindall *et al.* (2006).[3] As our results depend on benchmark electricity trade flows between California and neighboring states, we replace state-to-state electricity flows from IMPLAN with data from the National Renewable Energy Laboratory's ReEDS model (Short *et al.*, 2009). The ReEDS model simulates electricity flows between 136 Power Control Areas (PCAs) and represents existing transmission constraints. Bilateral U.S. state-to-country trade flows are based on the U.S. Census Bureau Foreign Trade Statistics State Data Series (U.S. Census Bureau, 2010). Bilateral exports and imports are taken from, respectively, the Origin of Movement (OM) and State of Destination (SD) data series.[4] The OM and SD data sets are available at the detailed 6-digit HS classification level, which permits aggregation to GTAP commodity categories.

We integrate GTAP, IMPLAN/SEDS, and U.S. Census trade data using constrained least-square optimization techniques. The data reconciliation strategy holds U.S. trade totals (by commodity) from GTAP fixed and minimizes the residual distance between estimated and observed U.S. Census state-to-country bilateral trade flows and estimated and observed SAM data from IMPLAN, subject to equilibrium constraints.

For this study, we aggregate the dataset to 15 U.S. regions, 15 regions in the rest of the world, and 14 commodity groups (see **Table 2**). Countries identified in the model include Brazil, Canada, China, India, Japan, Mexico and Russia. EU member states are included in a composite

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[2] The aggregation and reconciliation of IMPLAN state-level economic accounts needed to generate a micro-consistent benchmark dataset which can be used for model calibration is accomplished using ancillary tools documented in Rausch and Rutherford (2009).

[3] The IMPLAN Trade Flows Model draws on three data sources: the Oak Ridge National Labs county-to-county distances by mode of transportation database, the Commodity Flows Survey (CFS) ton-miles data by commodity, and IMPLAN commodity supply and demand estimates by county.

[4] The OM series does not necessarily represent production location as states with important ports of entry or exit might be over-represented relative to their actual trade specialization. Cassey (2006) uses additional destination-less estimates of state-level trade to test whether the origin of movement is a suitable proxy for production location. He finds that while there exist significant differences at the 6-digit commodity level for some states, the data is generally of good enough quality to represent the state of origin. Moreover, we argue that our relatively coarse aggregation of commodities and states is likely to smooth out this bias.

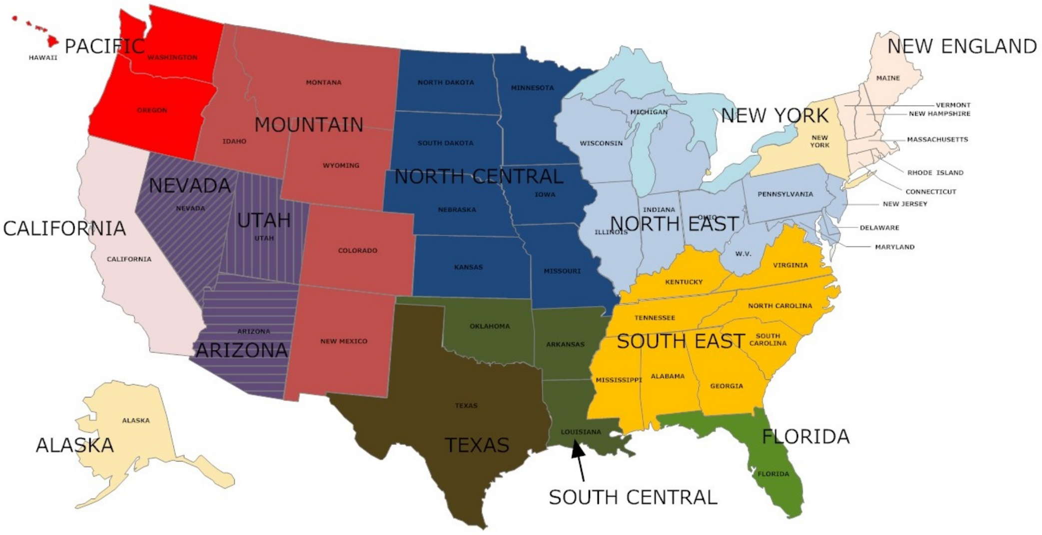

Figure 1. U.S. regional aggregation.

region and several other composites are included for other world regions. The composition of U.S. regions is illustrated in **Figure 1**. A separate region is included for some states, including California and states that trade electricity with California, but most U.S. regions include several states. Our commodity aggregation identifies five energy sectors and nine non-energy composites. Energy commodities identified in our study include Coal (COL), Natural gas (GAS), Crude oil (CRU), Refined oil (OIL), and Electricity (ELE), which allows us to distinguish energy goods and specify substitutability between fuels in energy demand. Electricity from fossil fuels, nuclear and renewables (including hydro) is considered in the model. Elsewhere, we distinguish five energy-intensive products—"Chemical, rubber, plastic products" (CRP), "Ferrous metals" (I_S), "Non-ferrous metals" (NFM), "Paper products and publishing" (PPP), Non-metalic minerals (NMM) and a composite of other energy-intensive manufacturing (EIS)—"Other manufacturing" (MAN), Agriculture (AGR), Transportation (TRN), and Services (SRV). A concordance between GTAP commodities and sectors identified in our study is provided in Table 2. Primary factors in the dataset include labor, capital, and fossil-fuel resources. Labor and capital earnings represent gross earnings denominated in 2004 U.S. dollars. The calculation of gross returns to each fossil-fuel resource is outlined in Section 3.2.5.

3.2 The Numerical Model

Our analysis draws on a multi-commodity, multi-region static numerical general equilibrium model of the world economy with sub-national detail for the U.S. economy. The key features of the model are outlined below.

Table 2. Regional and sectoral aggregation in model.

U.S. regions	International regions	Commodities (GTAP code)
New England	Russia	Agriculture (aggr.)
New York	China	Coal mining (COA)
South East	India	Natural gas extraction (GAS)
North East	Japan	Crude oil (OIL)
Florida	Rest of Americas	Electricity* (ELY)
South Central	Rest of Europe and Central Asia	Refined oil* (P_C)
North Central	Dynamic Asia	Paper products, publishing* (PPP)
Texas	Rest of East Asia	Chemical, rubber, plastic products* (CRP)
Mountain	Australia and Oceania	Ferrous metals* (I_S)
Pacific	Middle East	Metals* (NFM)
California	Africa	Non-metallic minerals* (NMM)
Alaska	Europe	Transportation (aggr.)
Nevada	Canada	Other energy-intensive industries (aggr.)
Utah	Mexico	Services (aggr.)
Arizona	Brazil	Manufacturing (aggr.)

Note: * denotes sectors covered in the California ETS.

3.2.1 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, crude oil, and land (R_{ir}), and produced intermediate inputs (X_{jir}):[5]

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

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 ={CRU, COL, GAS}), OIL, ELE, AGR, and non-energy industries (indexed by n ={TRN,EIS, SRV,CRP,I_S,NFM,NMM,PPP,MAN}). All industries are characterized by constant returns to scale (except for fossil fuels, AGR, and renewables 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 A1-A6**.

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

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

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[5] 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.

where α, ν are share coefficients of the CES function and $\sigma^R_{fr} = 1/(1-\rho^R_{fr})$ 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:

$$V_{fr} = L_{fr}^{\beta_{fr}} K_{fr}^{1-\beta_{fr}} \tag{3}$$

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:

$$Y^v_{ir} = \min\left(L^v_{ir}, K^v_{ir}, R^v_{ir}; X^v_{1ir}, \ldots, X^v_{Iir}\right) \,. \tag{4}$$

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:

$$G_r = \min(G_{1r}, \ldots, G_{ir}, \ldots, G_{Ir}) \,. \tag{5}$$

3.2.2 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):

$$U_r = \left[\mu_{cr} \min\left[g(C_{1r}, \ldots, C_{Ir}), \min(I_{1r}, \ldots, I_{Ir})\right]^{1/\rho_{cr}} + \gamma_{cr} N_r^{1/\rho_{cr}}\right]^{1/\rho_{cr}} \tag{6}$$

where μ and γ are CES share coefficients, and the elasticity of substitution between leisure and the consumption-investment 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 A6.

3.2.3 Supplies of Final Goods and Intra-US and International Trade

With the exception of crude oil, which is a homogeneous good, intermediate and final consumption goods are differentiated following the Armington assumption. For each demand class, the total supply of good i is a CES composite of a domestically produced variety and an imported one:

$$X_{ir} = \left[\psi^z \mathit{ZD}_{ir}^{\rho^D_i} + \xi^z \mathit{ZM}_{ir}^{\rho^D_i}\right]^{1/\rho^D{}_i} \tag{7}$$

$$C_{ir} = \left[\psi^c \mathit{CD}_{ir}^{\rho^D_i} + \xi^c \mathit{CM}_{ir}^{\rho^D_i}\right]^{1/\rho^D{}_i} \tag{8}$$

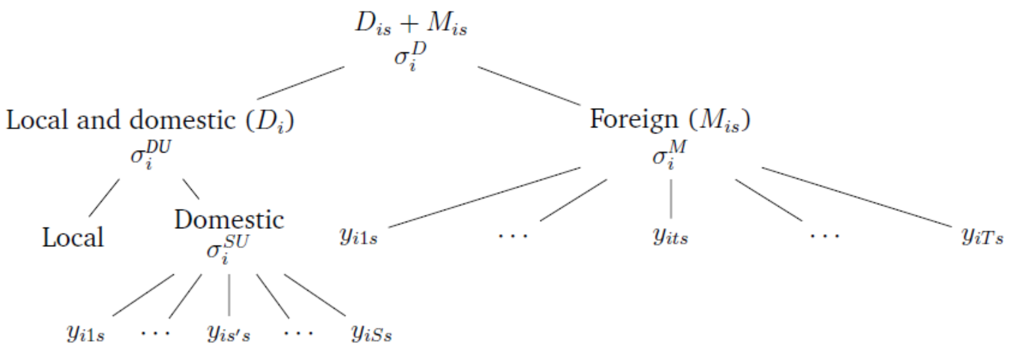

Figure 2. Aggregation of local, domestic, and foreign varieties of good i for U.S. region s.

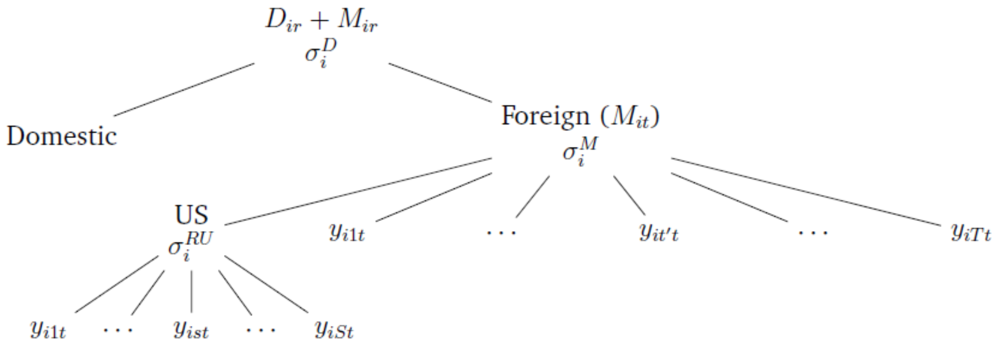

Figure 3. Aggregation of domestic and foreign varieties of good i for international region t.

$$I_{ir} = \left[\psi^i \, ID_{ir}^{\rho_i^D} + \xi^i \, IM_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{9}$$

$$G_{ir} = \left[\psi^g \, GD_{ir}^{\rho_i^D} + \xi^g \, GM_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{10}$$

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 and the imported varieties in these composites is $\sigma_i^D = 1/(1 - \rho_i^D)$.

The domestic imported varieties are represented by nested CES functions. We replicate a border effect within our Armington import specification by assuming that goods produced within the country are closer substitutes than goods from international sources. We include separate import specifications for U.S. 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:

$$M_{ir} = \begin{cases} \left[\left(\sum_s \pi_{ist}\, y_{isr}^{\rho_i^{RU}}\right)^{\rho_i^M/\rho_i^{RU}} + \sum_{t\neq r} \varphi_{itr}\, y_{itr}^{\rho_i^M}\right]^{1/\rho_i^M} & \textit{if} \quad r = t \\ \left[\sum_t \varphi_{itr}\, y_{itr}^{\rho_i^M}\right]^{1/\rho_i^M} & \textit{if} \quad r = s \end{cases} \tag{11}$$

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

$$D_{ir} = \begin{cases} \left[\left(\sum_{s\neq r} \pi_{isr}\, y_{isr}^{\rho_i^{SU}}\right)^{\rho^{DU_i}/\rho_i^{SU}} + \eta_{ir}\, y_i^{\rho_{ir}^{DU}}\right]^{1/\rho_i^{DU}} & \textit{if} \quad r = s \\ y_{ir} & \textit{if} \quad r = t \end{cases} \tag{12}$$

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 U.S. origins. **Figures 2** and **3** depict the nesting structures described by Eqs. (7)–(12).

3.2.4 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:

$$\max_{\{C_{ir},I_r,N_r\}} U_r \;\; s.t. \;\; p_r^i I_r + p_r^l N + \sum_i p_{ir}^c C_{ir} = p_r^k \overline{K}_r + p_r^{Vk}\overline{VK}_r + p_{fr}^R \overline{R}_{fr} + p_r^l \overline{L}_r + T_r \tag{13}$$

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, respectively.

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 U.S., malleable capital is perfectly mobile across U.S. 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 in Eqs. (1) and (4). Minimizing input costs for a unit value of output yields the unit cost indices (marginal cost) p_{ir}^Y and p_{ir}^{Yv}. 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: $GOV_r = TAX_r - \sum_r T_r - B_r$, 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:

$$GD_r = GOV_r / p_r^G \tag{14}$$

where p_r^G is the price of aggregate government consumption.

Market clearance equations for factors that are supplied inelastically are straightforward. The other market clearance equations are as follow:

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

$$D_{ir} = ZD_{ir} + CD_{ir} + ID_{ir} + GD_{ir}\,. \tag{15}$$

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

$$M_{ir} = ZM_{ir} + CM_{ir} + IM_{ir} + GM_{ir}\,. \tag{16}$$

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

$$\sum_s \sum_r y_{isr} + \sum_t \sum_r y_{itr} = \sum_s \sum_r y_{irs} + \sum_t \sum_r y_{irt}\,. \tag{17}$$

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.

3.2.5 Elasticities and Calibration

As customary in applied general equilibrium analysis, we use prices and quantities of the integrated economic-energy dataset for the base year (2004) to calibrate the value share and level parameters in the model. Response parameters in the functional forms which describe production technologies and consumer preferences are determined by exogenous elasticity parameters, the values of which are shown in Table 3. Armington trade elasticities in **Table 4** are based on GTAP estimates. Given the lack of empirical estimates for σ_i^{RU}, σ_i^{DU}, and σ_i^{SU} we use a "rule of thumb"

Table 3. 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*

Note: Substitution elasticity for fossil fuel, and nuclear resource factors are calibrated according to Eq. (18) 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.

which assumes the value at a given nest to be twice as large as its parent nest's. That is, we set the elasticity of substitution between local (within-state) and domestic (from other U.S. regions) goods (σ_i^{DU}) equal to twice the value of the elasticity of substitution between domestic and foreign goods (of σ_i^D).[6] Our model thus simulates a de-facto "border effect", and the within-country trade response will be larger than the international response. Note that, by assumption, the border effect is identical in each sector, which is unlikely to be the case in practice. We recognize that a robust exercise would require the empirical estimation of these elasticities in a structurally similar framework. Such an exercise is however beyond the scope of the present study and is left to further research. Section conducts a sensitivity analysis with respect to these parameters.

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

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[6] Estimates for σ_i^D are sourced from the GTAP database.

Table 4. Reference values of Armington elasticities in trade aggregation.

Parameter	Substitution margin	Source/Value
σ_i^D	Foreign—domestic (and local)	Based on GTAP, version 7
σ_i^M	Across foreign origins	Based on GTAP, version 7
σ_i^{RU}	Across U.S. origins for international regions	$2\,\sigma_i^M$
σ_i^{DU}	Local—domestic for U.S. regions	$2\,\sigma_i^D$
σ_i^{SU}	Across U.S. origins for U.S. regions	$2\,\sigma_{is}^{DU}$

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:

$$\zeta_f = \sigma_{fr}^R \frac{1-\alpha_{fr}}{\alpha_{fr}} \,. \tag{18}$$

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 U.S. 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 Energy Information Administration (2009). Following Paltsev *et al.* (2005) and Johnson (2010), we set the own-price elasticities of supply from hydro electricity and other renewable electricity equal to 0.5 and 2.7, respectively.

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).

3.3 Descriptive Analysis of the Data

Figure 4 displays, for each of California's trading partners, the CO_2 intensity of output, the share of CO_2 embodied in California's imports attributable to that region[7], and total regional CO_2 emissions (represented by bubble size). In aggregate, U.S. regions account for 23% of global CO_2 emissions. The next largest emitters are China (17%) and the EU (14%). California's emissions (not shown in Figure 4) are 5.5% of total U.S. emissions (and 2% of global emissions). The

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[7] To calculate embodied carbon, we use a multi-regional input-output decomposition technique ("Leontief inverse") which identifies the total (direct and indirect) amount of embodied emissions in each good.

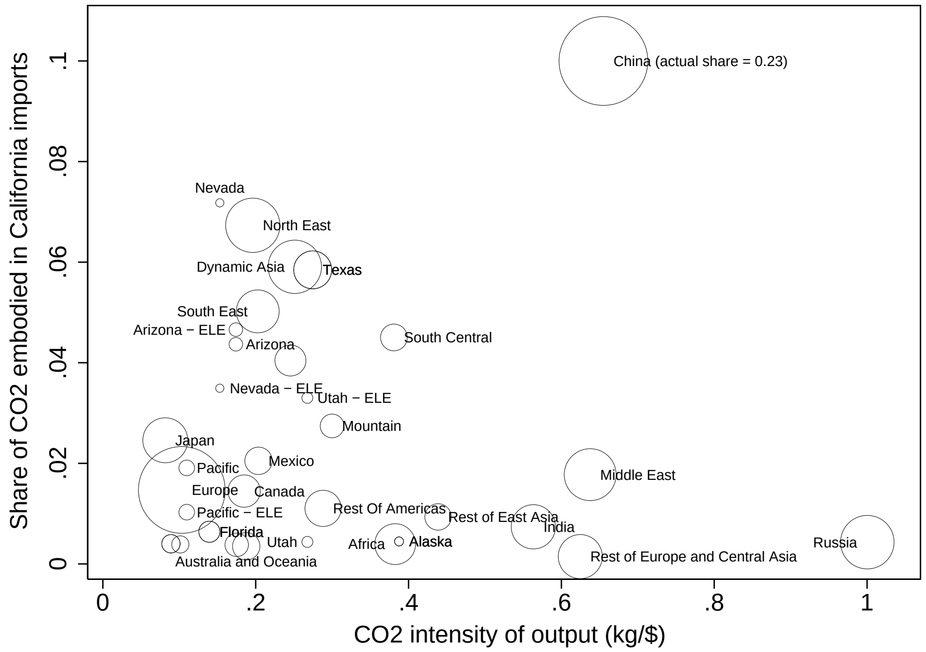

Figure 4. Share of embodied carbon in California's imports against carbon intensity of trading partner. Size of bubbles denotes benchmark CO_2 emissions. "ELE" denotes electricity trade.

largest sources of U.S. emissions are the North East (27% of U.S. emissions and 6% of global emissions), the South East (17% and 4%) and Texas (13% and 3%). As California's emissions are a small proportion of global emissions, large leakage rates can be consistent with small proportional changes in emissions in other regions. Regions that export electricity to California (Arizona, Nevada, Utah and the Pacific region) account for a small proportion of total emissions.

China accounts for the largest share of emissions embodied in California's imports, followed by the North East, Dynamic Asia and Texas. Electricity accounts for one-quarter of California's total imported emissions, mostly from Nevada (52%), Arizona (22%), and Utah (17%). Other major sources of imported emissions include Other manufacturing from China; Chemical, rubber and plastic products from China and Texas.

Electricity is a significant source of emissions in all regions. We calculate the average carbon intensity of electricity in each region by dividing the quantity of electricity in kilowatt hours (kWh) by emissions from fossil fuels used in electricity generation. Kilograms of CO_2 from each fossil fuel per kWh for U.S. regions are displayed in **Figure 5**. Compared to electricity generated in California, electricity from Utah is six times as carbon-intensive, electricity from Arizona and Nevada twice as carbon intensive, and electricity from the Pacific region is less carbon-intensive. In other regions, electricity in the Mountain, North Central and North East regions are relatively carbon-intensive. High carbon intensities in these (and other) regions are due to large shares of coal-fired generation. In contrast, emissions from natural gas account for 92% of total electricity emissions in California.

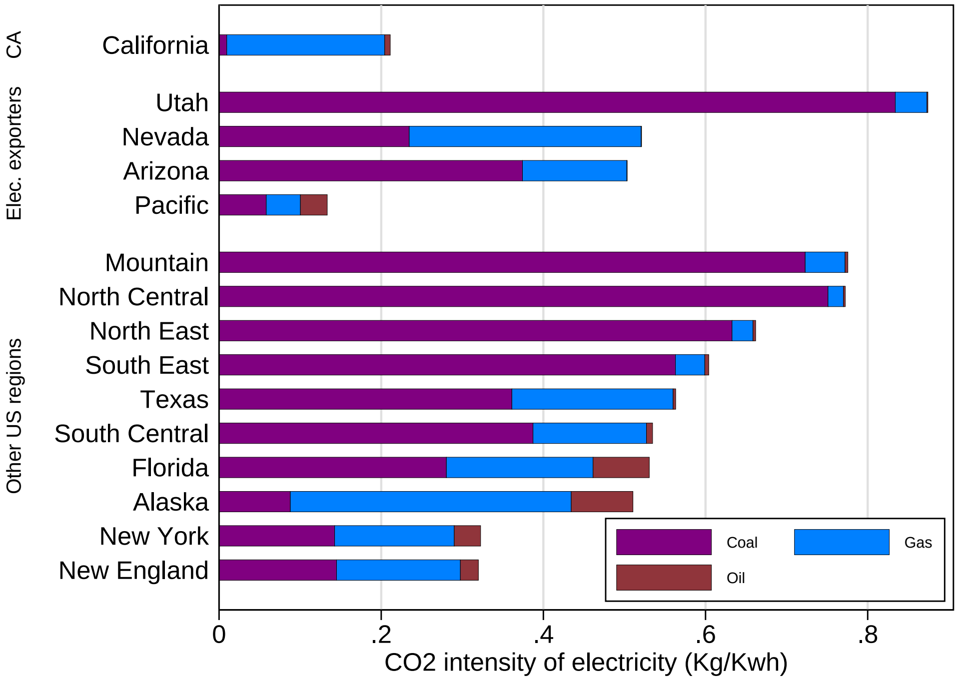

Figure 5. Kilograms of CO_2 emissions per Kwh of electricity production.

4. SCENARIOS AND MODELING RESULTS

4.1 Scenarios

We evaluate leakage from California's cap-and-trade program by considering six scenarios. Our first scenario, which we label "EU-ETS", simulates a cap-and-trade program in the EU. This scenario will serve as a point of comparison and allow the identification of the leakage risks of sub-national policies such as California's relative to national policies. The EU-ETS aims to reduce 2020 emissions by 21% relative to 2005 emissions. The actual reduction in EU emissions in 2020 due to the ETS will be influenced by, among other factors, regulations regarding the use of offsets, the banking of allowances for use in phase three of the EU-ETS, development of the EU's renewable portfolio standard, and whether or not the EU proceeds with plans to implement a more ambitious 2020 cap. We evaluate the impact of the EU-ETS, net of complementary measures, by imposing a cap that reduces EU emissions by 20% relative to benchmark emissions in our model. Reflecting current legislation, we apply the cap to emissions from Electricity; Oil refining; Chemical, rubber and plastic products; Ferrous metals; Metals nec; Mineral products; and Paper products and publishing.

The other five scenarios all include a cap on California's emissions. However, the EU emissions cap is still imposed in these scenarios and all impacts will be expressed relative to values in the the EU-ETS scenario. The reduction in California's emissions due to the cap-and-trade program will depend on emissions reduction due to complementary measures, such as California's Low Carbon Fuel Standard and Renewable Portfolio Standard, and the development of eligible offset programs. An analysis by CARB (2010) indicates that the reduction in California's emissions due to the cap-and-trade program will be 3.6% when offsets are used and 6.7% when there are no offsets.[8] We consider a cap that reduces California's emissions by 5% relative to the benchmark level. The cap is applied to Electricity; Oil refining; Chemical, rubber and plastic products; Ferrous metals; Mineral products; Paper products and publishing; and the use of refined oil and natural gas in other sectors and in final demand.

As noted in Section 2, California's legislation requires permits to be turned in for emissions embodied in imports and is similar to a tariff on out-of-state electricity. The effectiveness of this measure in reducing leakage will depend on how deliverers of electricity respond to the tariff and the application of the bill's measures to prevent resource shuffling. If out-of-state producers can reconfigure transmission so that low-carbon electricity is diverted to California and carbon-intensive electricity to other states, the tariff will have little impact on leakage. On the other hand, if electricity producers are unable to reroute supply and/or resource shuffling legislation is effective, the policy may lead to a large reduction in leakage in states producing (on average) relatively carbon-intensive electricity. We implement three scenarios to tease out the impact of different aspects of California's policy. In the $\text{CA}^{\text{noTariff}}$ scenario, we consider a cap on California's emissions without electricity tariffs or legislation to prevent resource shuffling. In our $\text{CA}^{\text{Shuffling}}$ scenario, we assume that there is an electricity tariff but electricity exporters can reduce the incidence of the tariff by reconfiguring supply so that low-carbon electricity is supplied to California (i.e., there is resource shuffling). This is modeled by assuming that, in each exporting state, all available renewable and nuclear electricity is supplied to California followed by, if required, electricity from gas and then electricity from coal. Tariffs are applied to the average carbon intensity of electricity exported from each state. As we do not consider transmission constraints, our $\text{CA}^{\text{Shuffling}}$ scenario represents the upper limit on changes in the composition of California's electricity imports when there is a tariff and resource shuffling is allowed.

In our $\text{CA}^{\text{noShuffling}}$ scenario, we calculate emissions embodied in imported electricity using emission coefficients in exporting regions from the benchmark data and set the elasticity of substitution between California's electricity imports from different regions (σ_i^{SU}) equal to zero. This scenario thus implicitly assumes that the ban on resource shuffling prevents importers from adjusting the composition of electricity to reduce CO_2 liabilities. Our $\text{CA}^{\text{noShuffling}}$ scenario includes all aspects of California's cap-and-trade policy and therefore is the most accurate representation of this legislation. In tariff scenarios, consistent with current legislation, the quantity of permits available for in-state production is reduced by the amount needed to cover emissions embodied in imported electricity.

We execute two additional scenarios to assess the impact of international trading of emission permits. One scenario, $\text{CA-TRD}^{\text{notariff}}$, allows trading of permits between the two systems without a tariff on California's imports of electricity. The other, $\text{CA-TRD}^{\text{noShuffling}}$, considers trading of

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[8] These calculations combine results from CARB (2010) Table 14 (p.38) and Table B-1 (p.97). Specifically, the CARB study estimates that policies will reduce California's emissions decrease by 18% relative to business as usual, and 20% of this decrease is due to the cap-and-trade policy when offsets are used and 37% when there are no offsets.

permits with California's electricity tariffs and no resource shuffling.

Finally, in the EU-ETS, $CA^{noTariff}$ and $CA^{noShuffling}$ scenarios, we implement a counterfactual exercise to distinguish the leakage occurring via the trade channel from that occurring through the fossil fuel price channel. Leakage due to trade is estimated by holding the price of fossil fuels constant in all regions and fossil fuel-price leakage is calculated as total leakage (simulated in our core scenarios) minus leakage due to trade. We choose this method to derive fossil-price leakage as fossil fuel price changes in one region will be driven by changes in excess demand for these commodities in other regions, which makes it difficult to design a simulation to isolate the impact of fossil fuel prices on leakage.[9]

4.2 Leakage Without Electricity Tariffs

Modeling results are summarized in **Tables 5** to **8**. CO_2 allowance prices, in 2004 dollars, are displayed in Table 5, as well as a summary of emissions reductions and leakage rates for leakage (i) to U.S. regions, (ii) to international regions, (iii) due to changes in electricity production, and (iv) total leakage. Leakage to each region is calculated as the increase in emissions in that region divided by the decrease in European emissions in the EU-ETS scenario, and the decrease in emissions in California in scenarios that consider California's cap-and-trade program (all others). In the scenarios that consider electricity tariffs, the reduction in California's emissions depends on the quantity of permits used for imported electricity. Consequently, the denominator for leakage calculations varies across scenarios.

Table 6 disaggregates leakage rates by region for each scenario and Table 7 disaggregates leakage among sectors for the core $CA^{noShuffling}$ scenario. To assess the contribution of changes in trade and fossil fuel prices, leakage due to each channel for aggregate regions for selected scenarios is reported in Table 8. By design the last panel of Table 8 replicates aggregate results reported in Table 6.

In the EU-ETS scenario, the allowance price is \$17 per metric ton of CO_2 (tCO_2) and the leakage rate to all regions is 21% of the reduction in EU emissions. Leakage rates to all regions are positive and the largest sources of leakage are Africa and China. U.S. emissions increase by 2% of the reduction in EU emissions. Table 8 indicates that around 60% of leakage occurs via the trade channel and 40% is due to changes in fossil fuel prices. Inspection of fossil fuel prices reveals a decrease in the composite price of fossil fuels and a decrease in the price of coal relative to the price of gas. Leakage via the trade channel is mainly due to increased EU imports of Electricity, Iron and steel, and Metals nec.

In the $CA^{noTariff}$ scenario, California's allowance price is \$12/tCO_2. The allowance price reduces California's electricity production by 21% and there is a decrease in the demand for natural gas. A large proportion of the reduction in California's electricity production is replaced by imported electricity, which results in high leakage to electricity exporters. The largest leakage sources are Arizona (24%), which experiences the largest increase in electricity exports to

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[9] Leakage may also result from the reallocation of capital across U.S. regions. In our modeling framework, results when capital was region specific were similar to those when capital was mobile across U.S. regions.

Table 5. Summary of results.

Scenario name	EU-ETS	$\text{CA}^{\text{noTariff}}$	$\text{CA}^{\text{Shuffling}}$	$\text{CA}^{\text{noShuffling}}$	$\text{CA-TRD}^{\text{noTariff}}$	$\text{CA-TRD}^{\text{noShuffling}}$
Permit trade with EU-ETS		no			yes	
Electricity tariff		no	yes		no	yes
Resource shuffling allowed			yes	no	yes	no
Carbon Price (2004\$/tCO_2)						
CA		11.6	22.3	65.3	15.9	20.0
EUR	16.5	16.4	16.4	16.4	15.9	20.0
Emissions change						
% of benchmark—in cap	-20.0	-5.0	-5.0	-5.0	-5.0	-5.0
% of CA benchmark—in CA		-5.0	-8.3	-13.3	-6.8	-4.9
% of CA benchmark—global		-3.2	-4.8	-13.4	-2.4	-14.5
Leakage rate (%)						
from individual policy						
Total	20.5	46.3	48.1	1.5	46.7	40.4
Electricity	15.5	48.6	42.8	-18.5	47.5	18.5
to US	1.4	52.5	48.7	-5.4	54.7	-5.6
International	19.0	-6.2	-0.6	6.9	-8.0	46.0
from CA and EU policies combined						
Total	20.5	21.9	23.1	17.5	23.0	18.9

Table 6. Leakage rates in % (based on domestic reduction).

	EU-ETS	$CA^{noTariff}$	$CA^{Shuffling}$	$CA^{noShuffling}$	$CA\text{-}TRD^{noTariff}$	$CA\text{-}TRD^{noShuffling}$
Total US	1.4	52.5	48.7	-5.4	54.7	-5.6
Total Elec. Exporters	0.0	53.3	38.1	-34.8	54.1	-35.1
Nevada	0.0	7.1	-2.7	-4.0	7.0	-3.7
Pacific	0.0	7.3	16.3	-4.9	7.6	-5.3
Utah	0.0	15.0	-1.9	-9.4	15.6	-9.6
Arizona	0.0	23.9	26.4	-16.5	24.0	-16.5
Total Rest of US	1.5	-0.9	10.6	29.3	0.6	29.5
North East	0.1	-5.0	-4.1	2.5	-4.3	0.6
North Central	0.2	-4.4	-4.3	-1.4	-4.2	-1.7
South East	0.4	-2.6	2.1	5.3	-2.0	4.5
South Central	0.0	-0.5	0.2	0.9	-0.2	0.2
New England	0.0	0.6	0.8	1.0	0.4	1.5
Alaska	0.0	0.7	0.7	1.2	0.7	1.2
New York	0.0	1.3	0.9	0.7	1.0	1.5
Florida	0.0	1.5	1.3	1.1	1.3	1.6
Mountain	0.3	1.7	4.9	8.5	1.4	12.2
Texas	0.2	5.7	7.9	9.5	6.5	7.9
Total International	19.0	-6.2	-0.6	6.9	-8.0	46.0
Russia	2.5	-1.3	-0.5	0.7	-1.5	5.6
Rest of Eur. /Centr. Asia	2.7	-0.9	-0.4	0.3	-1.4	6.7
China	3.5	-0.9	-0.3	0.6	-1.5	8.4
Rest of Americas	1.0	-0.7	-0.3	0.3	-0.7	2.4
Middle East	0.6	-0.6	0.0	0.9	-0.4	1.3
Dynamic Asia	1.4	-0.6	0.0	1.1	-0.6	3.1
India	0.9	-0.6	-0.2	0.2	-0.6	1.7
Japan	0.6	-0.5	-0.1	0.4	-0.4	1.0
Africa	3.8	-0.5	0.0	0.6	-1.3	9.6
Mexico	0.1	-0.4	-0.1	0.2	-0.3	-0.1
Australia and Oceania	0.8	-0.2	-0.1	0.1	-0.3	1.8
Rest of East Asia	0.3	-0.2	0.0	0.1	-0.2	0.6
Brazil	0.3	-0.2	0.0	0.2	-0.2	0.7
Canada	0.7	1.4	1.5	1.1	1.3	3.1
All regions	20.5	46.3	48.1	1.5	46.7	40.4

Table 7. Leakage by sector in the CA^{noShuffling} scenario.

	Elec. Exporters	Rest of US	US Total	International	Total
Electricity	-36.3	15.5	-20.9	2.3	-18.5
Natural gas	-0.4	-4.2	-4.6	0.0	-4.6
Coal	0.0	0.0	-0.1	0.0	-0.1
Petroleum and coal products (refined)	-0.1	2.3	2.3	0.0	2.3
Non-ferrous metals	0.0	0.0	0.0	0.0	0.0
Other manufacturing	0.0	0.0	0.0	0.1	0.1
Paper and Products and publishing	0.0	0.1	0.1	0.0	0.1
Ferrous Metals	0.0	0.2	0.2	0.0	0.2
Non-metallic minerals	0.0	0.3	0.3	0.0	0.3
Other energy intensive sectors	0.1	0.4	0.5	0.1	0.5
Agriculture	0.1	0.5	0.6	0.2	0.8
Services	0.1	0.9	1.0	0.2	1.2
Chemical, Rubber and Plastic products	0.0	3.6	3.6	0.4	4.0
Transportation	0.7	5.2	5.8	3.3	9.1
Final demand	1.1	4.6	5.8	0.3	6.1

California, and Utah (15%), the most carbon-intensive electricity exporter.

Decreasing electricity production in California and increasing production in electricity exporters decreases the price of natural gas and increases the price of coal. These price changes drive changes in emissions in other U.S. regions. In regions with a high proportion of electricity generated from coal, these price changes reduce emissions from electricity. The largest negative leakage rates are observed for the North Central and North East regions; however proportional changes in emissions is these regions are small. Although the Mountain region produces coal-intensive electricity, there is positive leakage to this region as the impact of the coal price is offset by increased electricity exports to regions supplying electricity to California.

Electricity emissions increase in regions producing a relatively large proportion of electricity from natural gas. In addition to increased electricity emissions, the large leakage rate for Texas (6%) is driven by increased exports of Chemical, rubber and plastic products to California. In the U.S., leakage to electricity exporters is 53% but leakage to other regions is -1%. Moreover, leakage to international regions is -6%, as positive leakage via the trade channel is more than offset by negative leakage due to changes in fossil fuel prices.

Finally, aggregate leakage in the the CA^{noTariff} scenario is 46%, more than double the leakage rate simulated for the EU-ETS. The large leakage rate is driven by increases in electricity production for export to California. Although there is negative leakage to regions that do not export electricity to California, our results indicate that without electricity tariffs California's cap-and-trade program will not be very effective at reducing emissions.

Table 8. Leakage due to fossil fuel price and trade channels (in %).

	EU-ETS	$CA^{noTariff}$	$CA^{noShuffling}$
Trade:			
Elec. Exporters	0.0	51.8	-36.1
Rest of US	1.4	2.7	13.4
International	11.0	7.2	5.7
All regions	12.4	61.7	-17.0
Fossil fuel prices:			
Elec. Exporters	0.0	1.5	1.4
Rest of US	0.1	-3.5	15.9
International	8.1	-13.4	1.2
All regions	8.1	-15.4	18.5
All channels:			
Elec. Exporters	0.0	53.3	-34.8
Rest of US	1.5	-0.9	29.3
International	19.0	-6.2	6.9
All regions	20.5	46.3	1.5

4.3 The Impact of Electricity Tariffs

4.3.1 Tariffs with Resource Shuffling

When there are tariffs on imported electricity but no resource shuffling provisions as in $CA^{Shuffling}$, the Pacific region has sufficient renewable and nuclear capacity to only export carbon-free electricity. Arizona can reduce the CO_2 intensity of electricity exported to California by 83%, whereas Nevada and Utah, which are the most CO_2-intensive suppliers of electricity to California, can only reduce theirs by 50%. As a result, relative to the $CA^{noTariff}$ scenario, Nevada and Utah export less electricity to California (and leakage to these regions decreases) whereas Arizona and the Pacific region export more (and leakage increases). Total leakage to electricity exporters decreases to 38% (from 54% in the $CA^{noTariff}$ scenario). However, leakage to other U.S. regions increases (from -1% to 11%) due to reduced demand for coal in Nevada and Utah and the higher permit price in the California. Leakage to international regions increases for the same reason. Aggregate leakage increases from 46% in the $CA^{noTariff}$ scenario to 48% in the $CA^{Shuffling}$ scenario, which indicates that electricity tariffs will not be an effective measure to reduce leakage if resource shuffling takes place.

4.3.2 Tariffs and No Resource Shuffling

We now consider a scenario that includes both the electricity tariff and a ban on resource shuffling, $CA^{noShuffling}$, as specified by California's cap-and-trade legislation. In this scenario, the allowance price is considerably higher at $65/tCO_2 and, due to the use of permits for imported electricity, the actual emissions reduction to take place within California is 13.4% (instead of 5%). Electricity production in California is on average less CO_2-intensive than imported electricity, so the policy increases the production of electricity within California at the expense of electricity imports. In aggregate, leakage to electricity exporters is -35%, which is driven by emissions reductions in Arizona (leakage of -17%) and Utah (-9%).

However, the negative leakage to electricity exporters is partially offset by positive leakage (29%) to other U.S. regions due to changes in both trade and fossil fuel prices (see Table 8). Leakage due to changes in fossil fuel prices is driven by a decrease in demand for refined oil in California and a decrease in demand for coal in regions exporting electricity to California, which ultimately increases emissions from transportation and electricity generation in other U.S. regions. The major sources of leakage to other U.S. regions via the trade channel are increased California's imports of Chemical, rubber and plastic products from Texas and the South Central region. Overall, positive leakage to other U.S. and international regions is mostly offset by negative leakage to electricity exporters and the aggregate leakage rate is 1.5%. To conclude, our results indicate that although the inclusion of imported electricity in the cap and a ban on resource shuffling significantly increase the price of CO_2 allowances and that leakage is in a large part simply further displaced (to the rest of the U.S. and internationally), the emissions reductions in electricity exporting states are sufficient to essentially eliminate total leakage.

4.4 Trading of Permits Between California and the EU

International trading of emissions permits equalizes permit prices across the two systems. The EU market for emissions permits is three times the size of that in California and the common permit price is close to the EU autarky price, but the California's electricity tariffs still have a non-negligible impact on the common permit price. Also, as trading changes permit prices in both California and the EU, leakage rates will be influenced by production and consumption changes in both regions.

In the CA-TRD$^{\text{noTariff}}$ scenario, abatement possibilities are cheaper in California than in Europe, and California reduces its emissions by 6.8% instead of 5%. Relative to the corresponding case without trading, permit prices increase to \$16 (from \$12). Leakage to U.S. regions increases (from 53% to 55%), mainly due to an increase in California electricity imports. Leakage to international regions falls due to the decrease in the permit price in the EU. The overall leakage rate from the combined policies increases from 21% to 23%.

When there is an electricity tariff and no resource shuffling, permit trading decreases the price of emissions rights in California (from \$65) and increases it in the EU (from \$16) to \$20. The decrease in the permit price in California decreases the tariff on imported electricity and ultimately increases emissions in regions exporting electricity to California. However, there is also a decrease in emissions abatement within California (the denominator for leakage calculations), so there is only a small change in leakage to electricity exporters in the CA-TRD$^{\text{noShuffling}}$ scenario relative to the CA$^{\text{noShuffling}}$ case. The decrease in the price of coal increases electricity emissions in other regions so leakage due to changes in electricity production is 19%, even though there is negative leakage to regions exporting electricity to California. Allowing permit trade between the EU and California again results in a small increase in leakage

Table 9. Leakage rates (%) and CO_2 prices (2004\$/tCO_2) for alternative Armington elasticity values.

	σ_i^{DU} — σ_i^{SU}				
	Base-Base	Low-Base	Base-Low	Low-Low	High-High
$CA^{noTariff}$					
Carbon Price (\$/tCO_2) - CA	11.6	14.2	11.7	14.3	8.0
Leakage rate (%)					
Total	46.3	31.4	43.8	30.5	70.5
Electricity	48.6	31.4	45.8	30.1	68.3
to US	52.5	35.7	48.6	33.5	80.8
International	-6.2	-4.3	-4.8	-3.0	-10.3
$CA^{noShuffling}$					
Carbon Price (\$/tCO_2) - CA	65.3	68.1	55.7	56.6	37.7
Leakage rate (%)					
Total	1.5	10.2	3.2	6.6	11.0
Electricity	-18.5	-6.7	-15.4	-10.1	-16.1
to US	-5.4	3.5	-1.9	1.3	12.2
International	6.9	6.7	5.1	5.3	-1.2

Note: "Base" elasticity values equal those in our core scenarios ($\sigma_i^{DU} = 2\sigma_i^M$ and $\sigma_i^{SU} = 4\sigma_i^M$). "Low" elasticity values are half base values ($\sigma_i^{DU} = \sigma_i^M$ and $\sigma_i^{SU} = 2\sigma_i^M$). "High" elasticity values are twice as large as base values ($\sigma_i^{DU} = 4\sigma_i^M$ and $\sigma_i^{SU} = 8\sigma_i^M$).

from the combined systems (from 18% to 19%). Thus, we have found that from the EU's perspective, permit trade with a sub-national region such as California - whose economy is tightly integrated with other states' - leads to a modest increase in overall leakage rates, whether or not electricity tariffs are implemented.

4.5 Sensitivity Analysis

A key driver of our results is that changes in California have larger impacts on U.S. regions than international regions. Accordingly, we consider "Low" and "High" alternative values for elasticities governing substitutability in U.S. demand between domestic and imported production (σ_i^{DU}), and among imports from U.S. regions (σ_i^{SU}). In our base case, $\sigma_i^{DU} = 2\sigma_i^M$ and $\sigma_i^{SU} = 4\sigma_i^M$ (where σ_i^M is the elasticity of substitution for good i from imports from international regions). Our low alternative values for σ_i^{DU} and σ_i^{SU} are half the base values of these elasticities. We believe the low alternative for σ_i^{DU} ($= \sigma_i^M$) is the lower bond on this elasticity, as international goods should not be closer substitutes to California's goods than goods from other states. In high variant cases, we double base values for σ_i^{DU} and σ_i^{SU}.

Leakage rates and permit prices for aggregated regions in the $CA^{noTariff}$ and $CA^{noShuffling}$ scenarios are presented in **Table 9**. The first component of case labels convey values for σ_i^{DU} and the second component values for σ_i^{SU}. In the $CA^{noTariff}$ scenario, decreasing σ_i^{DU} reduces substitution away from California's consumption towards imported electricity, which reduces leakage to electricity exporters. A lower value of σ_i^{DU} also means that a higher permit price is required to meet the emissions cap, which increases leakage to other regions. The net effect is a small increase in aggregate leakage in the Low-Base case relative to our core case. Decreasing the value of σ_i^{SU} (Base-Low) has only a minor impact on leakage and the permit price as changes in relative prices of imports from different sources are small. Importantly, the conclusion that leakage to the U.S. is larger than international leakage holds even in the Low-Low case in which no border effect is generated by the calibration of Armington elasticities. Increasing import elasticities (High-High) decreases abatements costs and the permit price, and increases substitution towards imported electricity. As a result there is a larger increase in leakage to electricity exporters, which is partially offset by a decrease in leakage to other regions. Overall, we find that despite uncertainty in the estimates of total leakage (it ranges from 31 % to 71%), it remains in all cases higher than leakage estimates generally found for national policies.

In the $\text{CA}^{\text{noSuffling}}$ scenario, as σ_i^{SU} is zero for California's electricity imports, high and low cases for this elasticity do not have a large impact on changes in electricity emissions, so leakage in the Base-Low case (3%) is similar to that in the Base case (2%). Leakage in the Low-Low and High-High cases is 7% and 11% respectively, and in all cases leakage rates remain much lower than in the $\text{CA}^{\text{noSuffling}}$ scenario. Overall, the sensitivity analysis indicates that our findings are reasonably robust to alternative elasticity values and that the results are more sensitive to variability in scenario assumptions than alternative Armington elasticity values.

5. CONCLUSIONS

This paper considered leakage from California's cap-and-trade program, the first such policy to be legislated in the U.S. Our analysis employed a global model of economic activity and energy systems that identified 15 U.S. regions and 15 regions in the rest of the world. The framework explicitly modeled bilateral trade flows among all regions.

Key features of California's cap-and-trade policy include the requirement that allowances must be surrendered for emissions embodied in imported electricity, which is similar to an import tariff, and provisions to prevent resource shuffling. If these features were not included in the policy, leakage was found to be 46% of the decrease in emissions in California. California's potential for reducing emissions alone would thus be limited. This estimate was driven by leakage of 54% to regions exporting electricity to California. There was negative leakage to other U.S. and international regions largely due to a decrease in the relative price of natural gas. Leakage remained significant when electricity tariffs were included but out-of-state generators could lower the incidence of the tariff by rerouting electricity transmission so that less carbon-intensive electricity is supplied to California. If such resource shuffling is banned, however, leakage to electricity exporters was -35%. Increases in leakage to other U.S. and international regions compensate for this decrease and total leakage is just 2%. These finding indicate that California's cap-and-trade program will lead to very little leakage. This conclusion hinges on the enforcement of provisions to prevent resource shuffling: without them, electricity tariffs may not be able to prevent substitution towards imported electricity. A corollary of this conclusion is that electricity tariffs are an effective way of expanding the scope of the program, although permits used for imported electricity increased the reduction in California's emissions beyond that mandated by the cap and increased the price of permits significantly. Another interesting finding was that leakage to international regions was small, as California is more closely linked to other U.S. states than international regions. Finally, we considered the possibility of allowing trading of emission permits between California and the EU-ETS, and found it to result in a small increase in aggregate leakage from the two systems.

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APPENDIX A: Structure of Production and Consumption Technologies

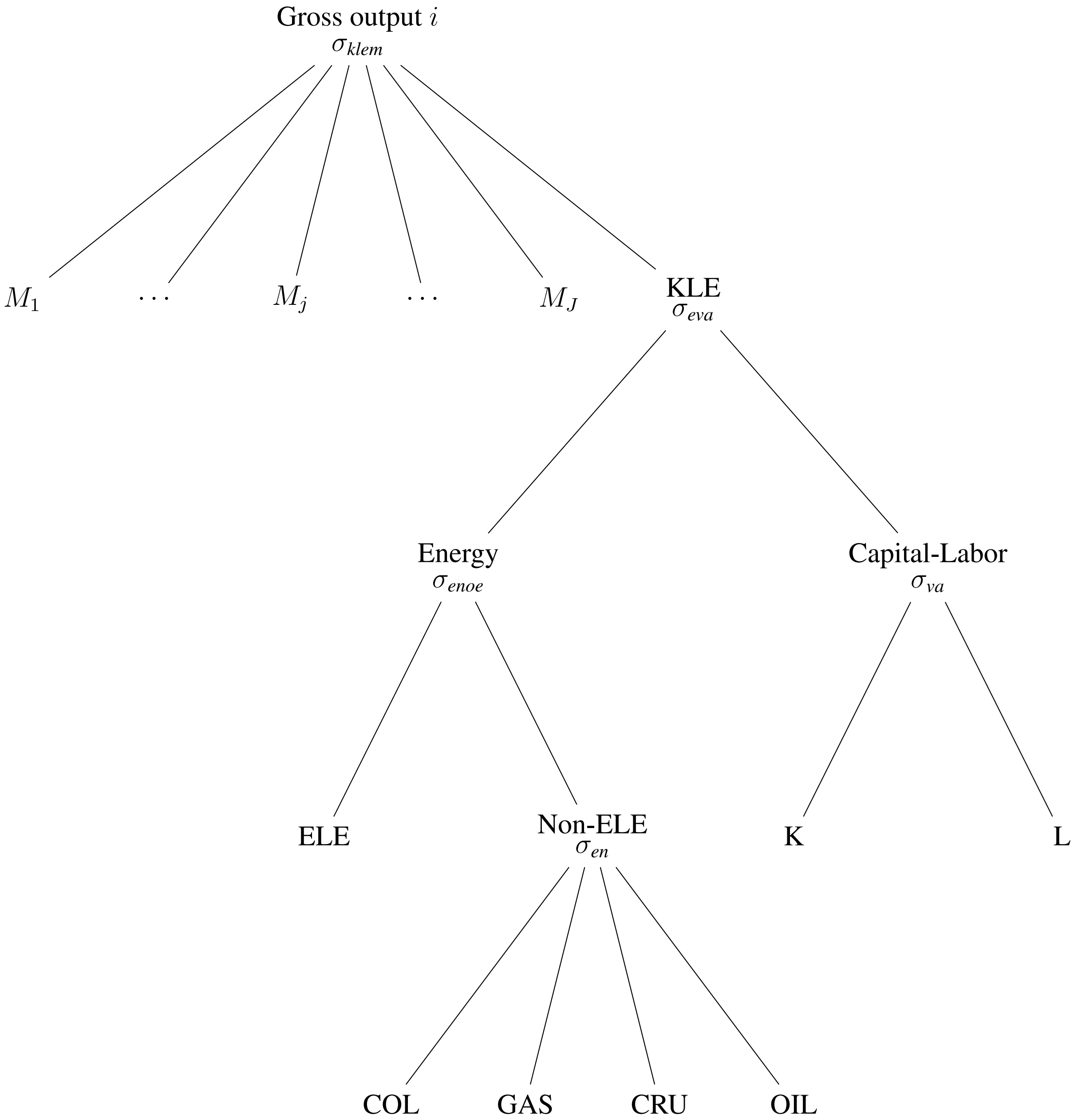

Figure A1. Structure of production for $i \in \{$TRN,EIS,SRV,CRP,I_S,NFM,NMM,PPP,MAN$\}$.

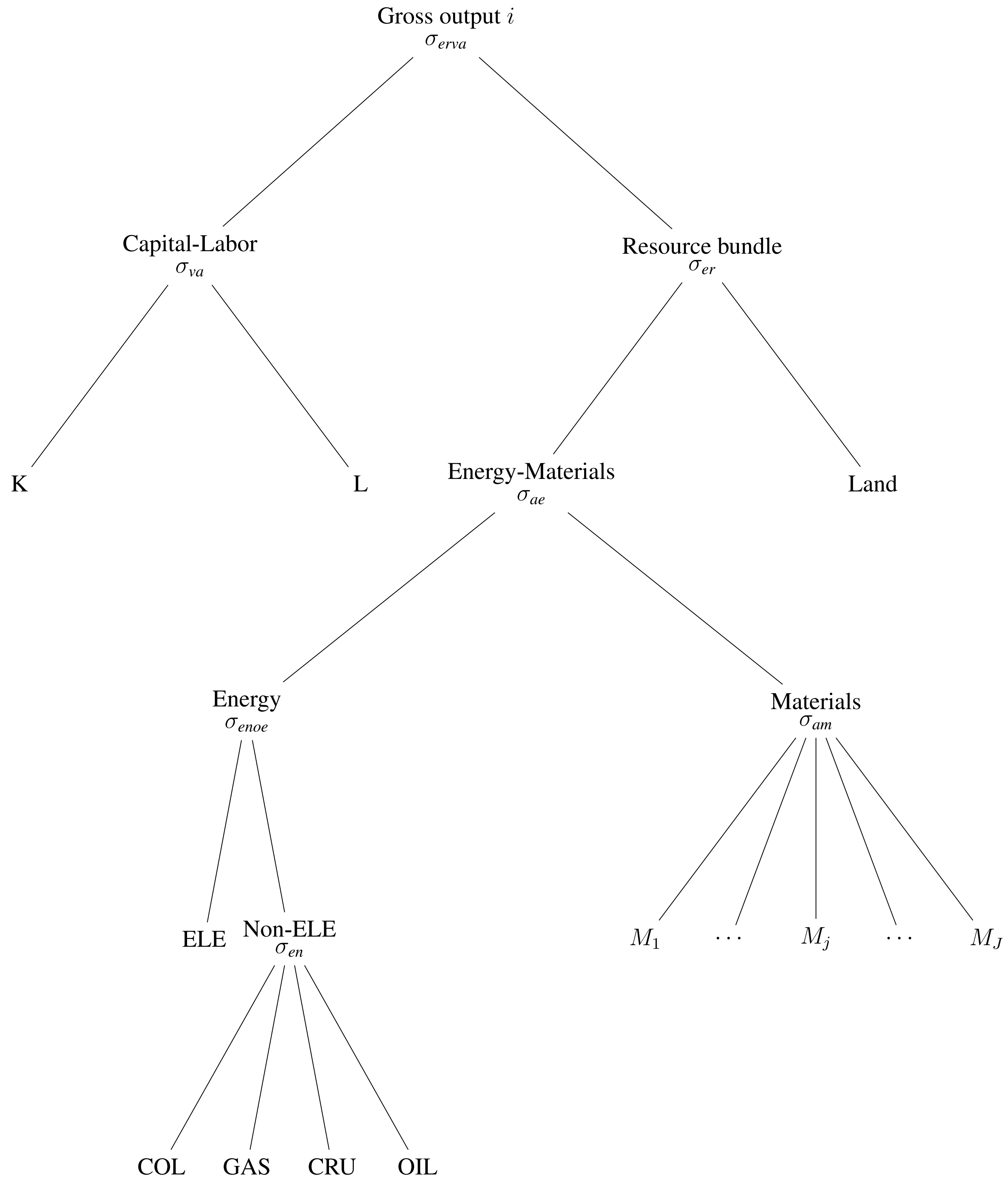

Figure A2. Structure of production for $i \in \{\text{AGR}\}$.

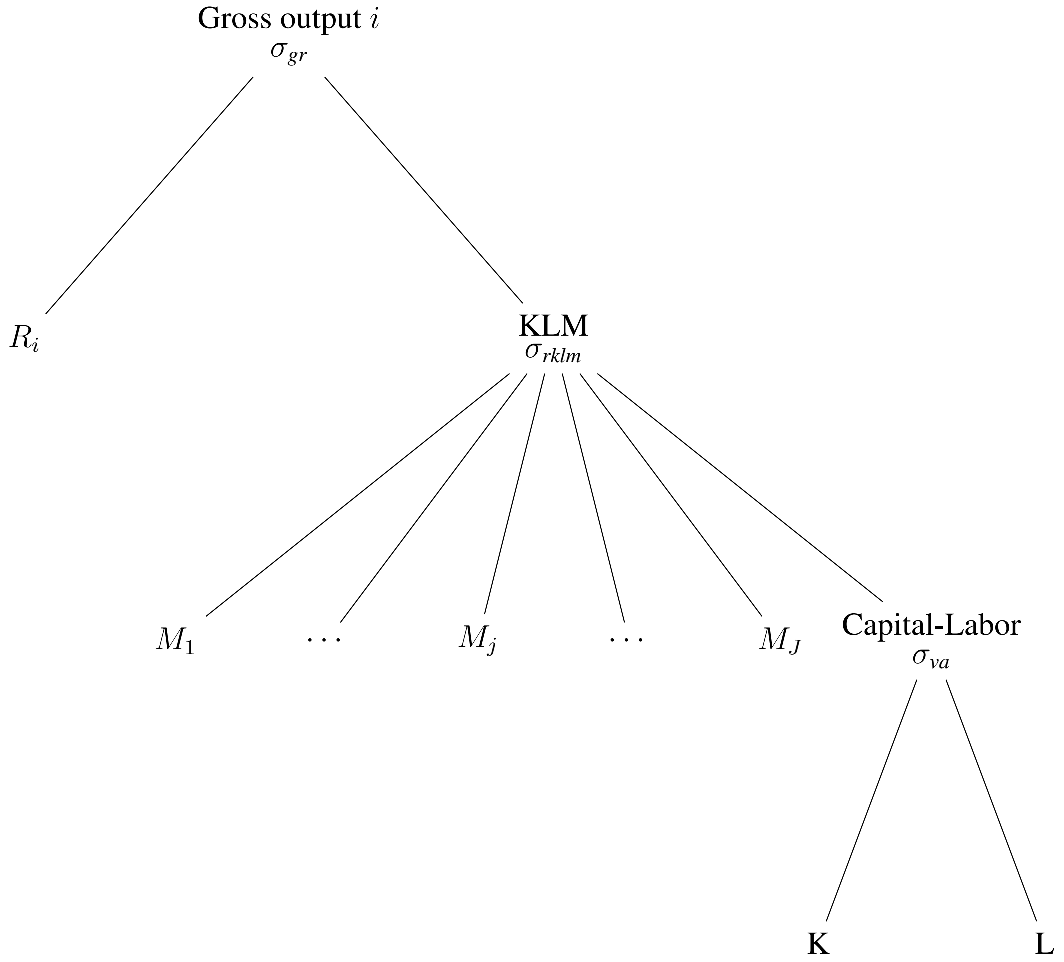

Figure A3. Structure of primary energy sectors $i \in \{$COL,CRU,GAS$\}$.

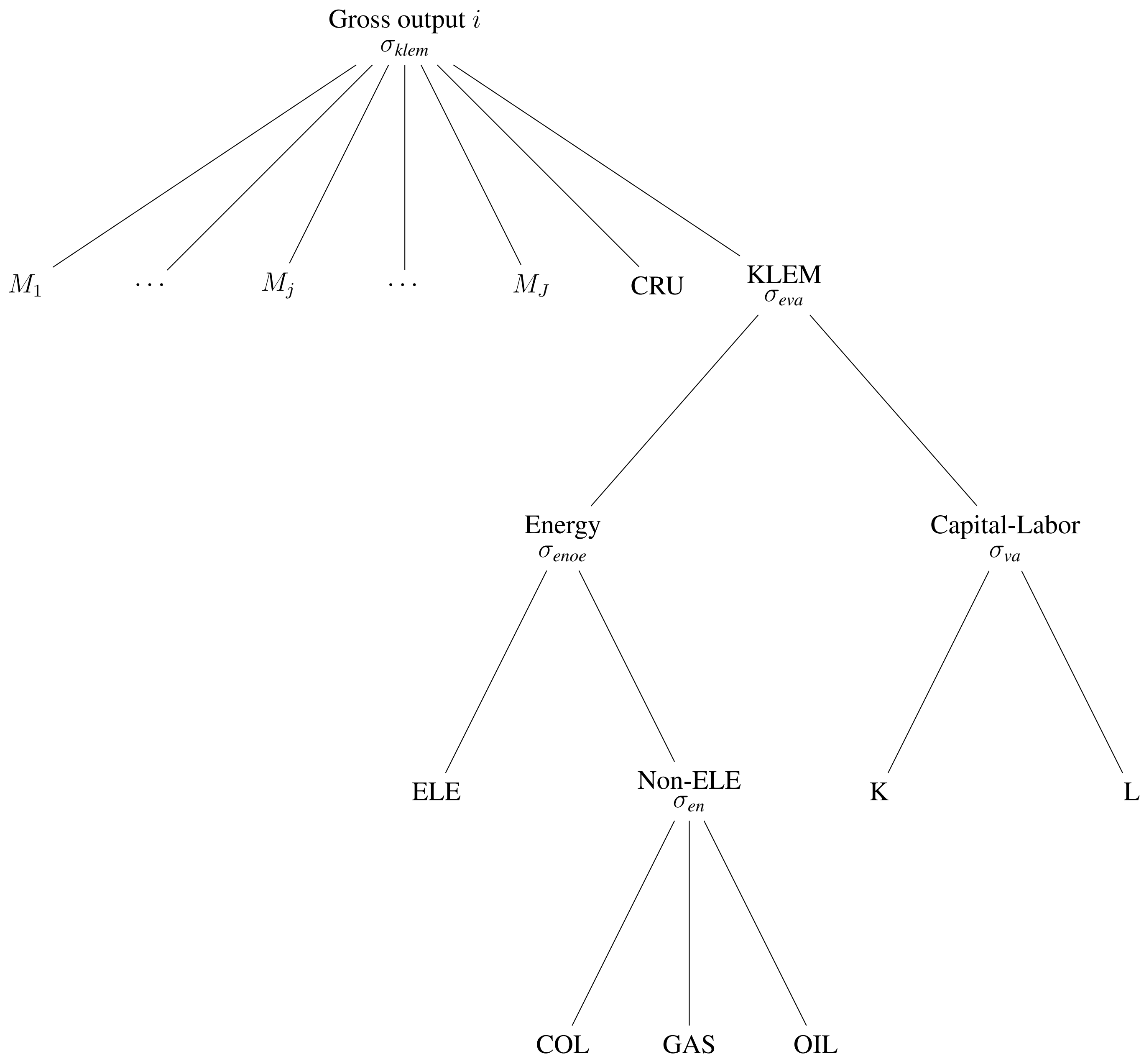

Figure A4. Structure of production for $i \in \{\text{OIL}\}$.

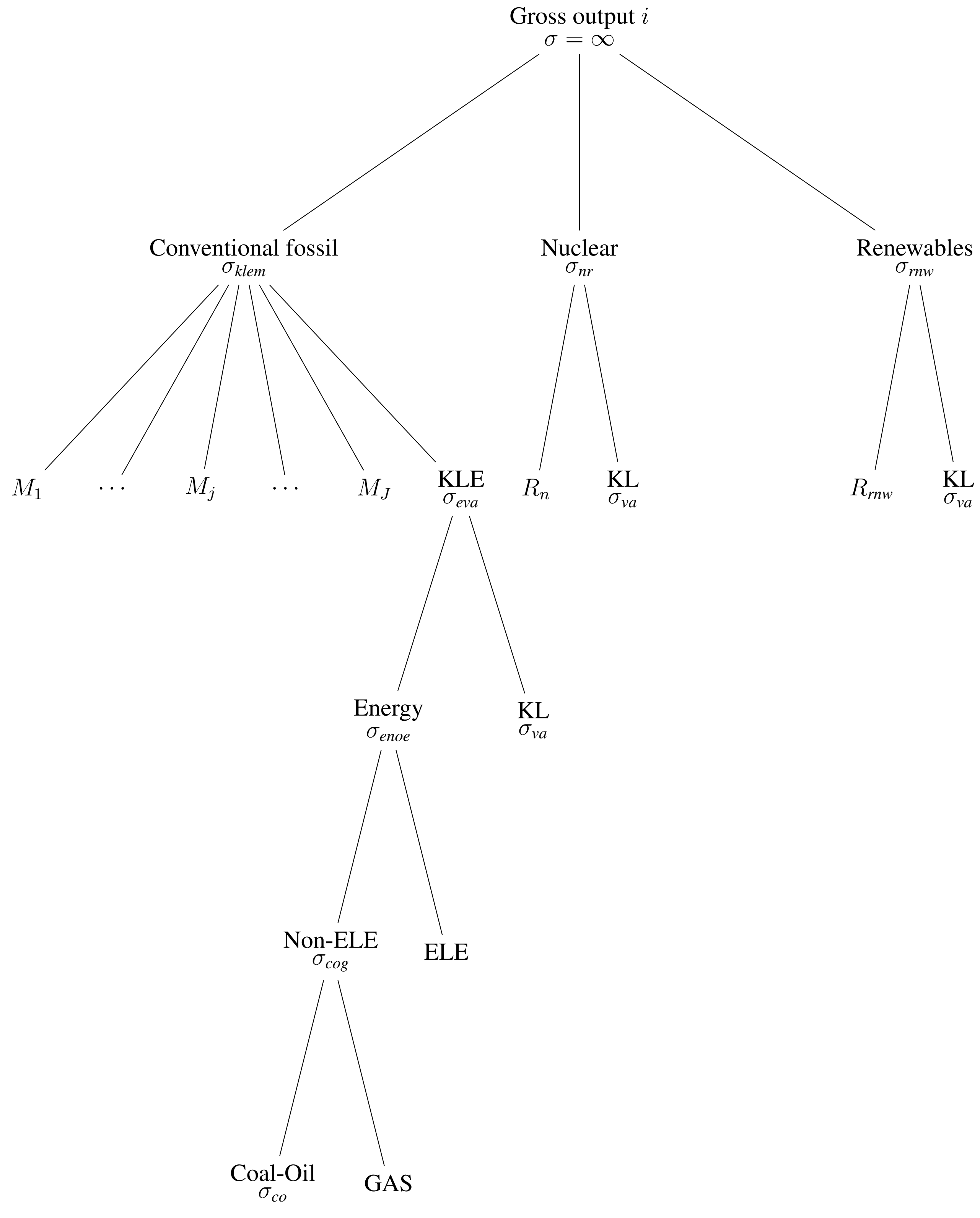

Figure A5. Structure of electricity production $i \in \{\text{ELE}\}$.

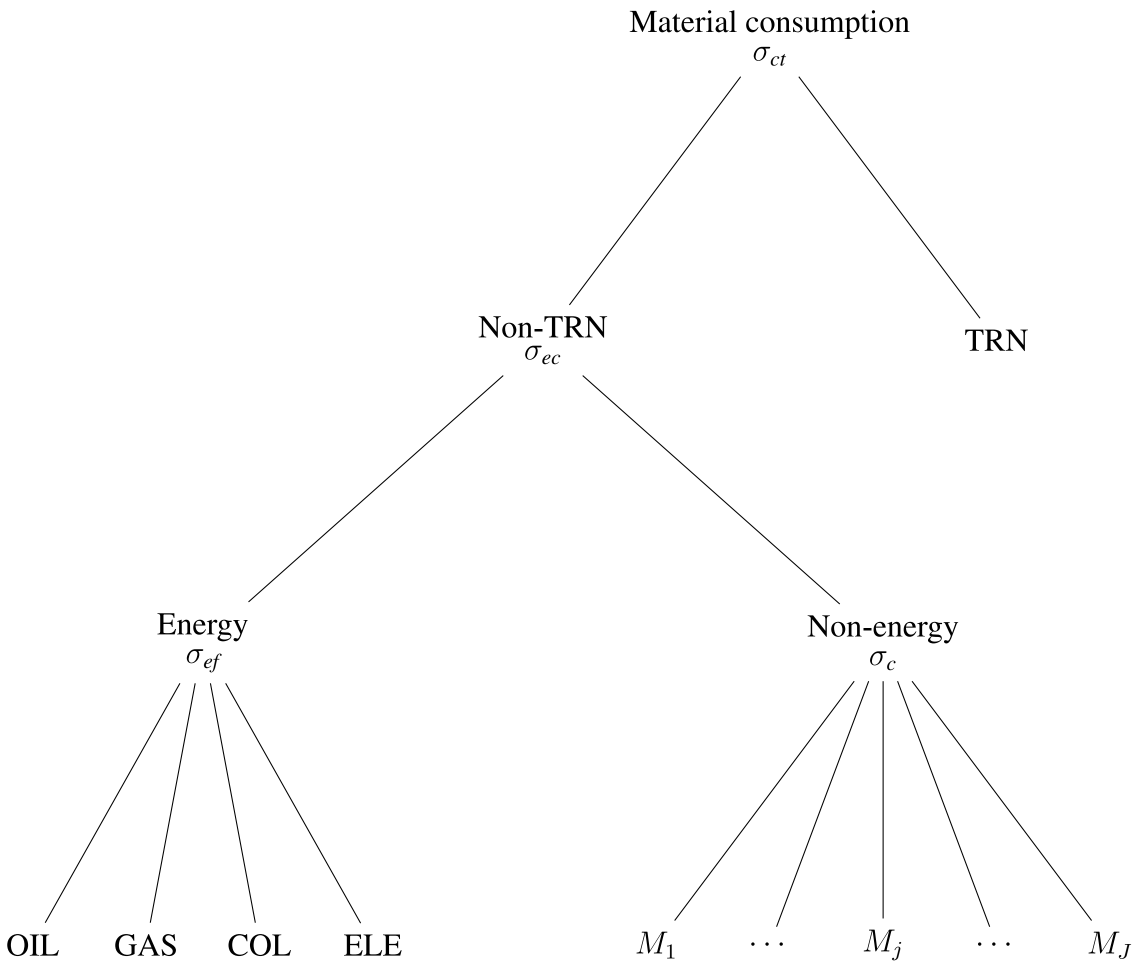

Figure A6. Structure of private material consumption.

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