Leakage from sub-national climate initiatives*

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Abstract

This paper considers leakage from sub-national climate policies using California's cap-and-trade program as a representative example. Our analysis is built on a global model of economic activity and energy systems that identifies 15 US regions and 15 regions in the rest of the world. As California's cap-and-trade policy requires electricity importers to surrender emissions allowances, leakage depends on the ability of out-of-state generators to reconfigure transmission to reduce the carbon intensity of electricity supplied to California. If exporters can dispatch carbon-free electricity to California and carbon-intensive electricity is rerouted to other markets, leakage is 47% of the decrease in emissions in California. If exporters are unable to adjust the carbon intensity of electricity supplied to California, as imported electricity is relatively carbon intensive, there is negative leakage to regions supplying electricity to California and the aggregate leakage rate is 5%. We also observe negative leakage to some regions due to changes in fossil fuel prices and that the impact of the trading of emissions permits between California and the EU depends on the ability of out-of-state generators to reconfigure electricity supply.

Keywords: Leakage, sub-national climate policy, tradable permits, embodied emissions, computable general equilibrium modeling.
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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 prices and capital 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 countries. 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 capital migration from unconstrained regions to constrained regions (Fullerton, Karney and Baylis, 2011).

With federal initiatives to curb GHGs stalling in the US, sub-national polices have received greater focus. Sub-national initiatives can generate higher leakage rates than federal policies, as intra-national trade is generally much larger than trade between regions in different countries (Anderson and van Wincoop, 2003). This allows greater scope for leakage through the trade and, to the extent that fossil fuel markets are linked, changes in fossil fuel prices. Additionally, for geographical reasons, there are greater possibilities for a territory to import electricity under a sub-national agreement than under a federal policy.

To date, two sub-national cap-and-trade policies have been legislated in the US. 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 emissions permits among states. Second, a cap-and-trade program on emissions from

electricity generation and certain industrial industries will operate in California beginning in 2013. Transport and other fuels will be included in the program from 2015, by which time the cap will cover an estimated 85% of California's GHG emissions sources. The policy includes a border carbon adjustment (BCA) measure for electricity imports from both domestic and international sources. At the time of writing, California's policy is the only economy-wide cap-and-trade program to be enacted in the US 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 permit trade 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 US 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 one 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 (CGE) model calibrated to a dataset which includes 15 US states or regions and 15 countries or regions in the rest of the world. The model tracks bilateral trade among all regions, including trade among US regions and trade between US regions and international regions. Due to its detailed treatment of trade flows, the 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 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 later that month.

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 pa-

per manufacturing. Requiring allowances to be turned in for emissions embodied in imported electricity is similar to imposing an electricity tariff. A key difference, however, is that requiring allowances for imported electricity will increase the demand for and price of permits, which will not occur under a tariff.

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 US, 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 (Mulkern, 2011).

CARB (2011, Subarticle 12, p. A-153) also sets out conditions for linking the Californian program to other schemes. Once an external ETS has been approved by the CARB, compliance instruments issued by other programs may be used to meet Californian 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 US 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 Californian authorities have been in close contact with staff in some Canadian provinces, California is the 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).

[1] Several regions are members of the WCI as observers. Observers include the US 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
US states	IMPLAN (2008) and gravity model (Lindall et al., 2006)
US state-to-country bilateral trade flows	Origin of Movement (OM) and State of Destination (SD), US Census Bureau (2010)
Physical energy flows and energy prices	
international regions	GTAP (2008)
US states	State Energy Data System (SEDS), EIA (2009)
Trade elasticities	GTAP (2008) and own calibration
Energy demand and supply elasticities	Paltsev et al. (2005)

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 datset merges detailed state-level data for the US 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 (SAM) in our hybrid dataset are based on data from the Global Trade Analysis Project (GTAP, 2008), IMPLAN (IMpact analysis for PLANning) data (IMPLAN, 2008), and US state-level accounts on energy balances and prices from the EIA (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 US states (and the District of Columbia). The dataset includes input-output tables for each state that identify

509 commodities and 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 (EIA, 2009).[2]

Data for trade between regions outside of the US are taken from GTAP and reflect UN-COMTRADE bilateral flows. Bilateral state-to-state trade data in the IMPLAN database are derived using a gravity approach described in Lindall, Olson and Alward (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 modeled data from National Energy Renewable 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 US state-to-country trade flows are based on the US Census Bureau Foreign Trade Statistics State Data Series (US 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 US Census trade data by using least-square opti-

[2] Aggregation and reconciliation of IMPLAN state-level economic accounts 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.

mization techniques. Our data reconciliation strategy is to hold US trade totals (by commodity) from GTAP fixed and to minimize the residual distance between estimated and observed US 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 US 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 region and several other composites are included for other world regions. The composition of US 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 US 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 and nuclear and hyrdo generation 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" (PPP), and a composite of 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 US dollars. The calculation of gross returns to each fossil-fuel resource is outlined in Section 3.2.5.

Table 2: Regions, commodity classifications and mappings in the model.

Region	Aggregated region	GTAP commodity	Aggregated commodity
New England	NENG	Processed rice	AGR
New York	NY	Grains	AGR
South East	SEAS	Sugar	AGR
North East	NEAS	Plant-based fibers	AGR
Florida	FL	Forestry	AGR
South Central	SCEN	Fishing	AGR
North Central	NCEN	Sugar cane, sugar beet	AGR
Texas	TX	Beverages and tobacco products	AGR
Mountain	MOUN	Bovine meat products	AGR
Pacific	PACI	Bovine cattle	AGR
California	CA	Dairy products	AGR
Alaska	AK	Crops	AGR
Nevada	NV	Food products	AGR
Utah	UT	Meat products	AGR
Arizona	AZ	Oil seeds	AGR
		Vegetables, fruit, nuts	AGR
Russia	RUS	Vegetable oils and fats	AGR
China	CHN	Animal products	AGR
India	IND	Coal mining	COL
Japan	JPN	Natural gas extraction	GAS
Rest of Americas	LAM	Crude oil	CRU
Rest of Europe and Central Asia	ROE	Electricity	ELE
Dynamic Asia	ASI	Refined oil	OIL
Rest of East Asia	REA	Air transport	TRN
Australia and Oceania	ANZ	Transport	TRN
Middle East	MES	Water transport	TRN
Africa	AFR	Communication	SRV
Europe	EUR	Construction	EIS
Canada	CAN	Metal products	EIS
Mexico	MEX	Motor vehicles and parts	EIS
Brazil	BRA	Minerals	EIS
		Chemical, rubber, plastic products	CRP
		Ferrous metals	I_S
		Metals	NFM
		Mineral products	NMM
		Paper products, publishing	PPP
		Leather and wood products	MAN
		Machinery and equipment	MAN
		Manufactures	MAN
		Transport equipment	MAN
		Textiles	MAN
		Wearing apparel	MAN
		Dwellings	SRV
		Insurance	SRV
		Business and financial services	SRV
		Recreational and other services	SRV
		Other Services	SRV
		Trade	SRV
		Water	SRV

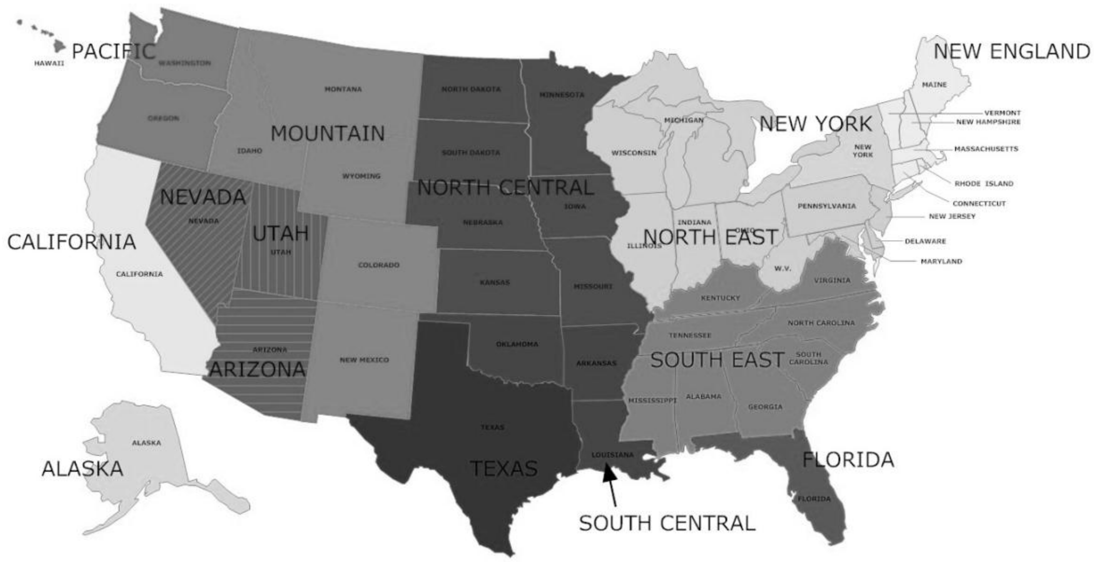

Figure 1: Aggregated regions for the US.

3.2 The numerical model

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

3.2.1 Production and transformation technologies

For each industry ($i = 1, \ldots, J$) 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}), $j = i$:[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 five types of production activities in the model: fossil fuels (indexed by f ={CRU, COL, GAS}), refined oil (OIL), electricity (ELE), agriculture (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 and AGR which are produced subject to decreasing returns to scale) and are traded in perfectly competitive markets. Nesting structure for each type of production system are depicted in Figures A 1-A 5.

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

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

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 of labor and capital:

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

where β is the labor share.

[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.

We adopt a putty-clay approach where 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:

$$Y_{ir}^{v} = \min\left(L_{ir}^{v}, K_{ir}^{v}, R_{ir}^{v}; X_{1ir}^{v}, \ldots, X_{Iir}^{v}\right) . \tag{4}$$

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 $g(\cdot)$ is a CES composite of energy and non-energy goods whose nesting structure is depicted in Figure A 6.

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:

$$X_{ir} = \left[\psi^z\, ZD_{ir}^{\rho_i^D} + \xi^z\, ZM_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{7}$$

$$C_{ir} = \left[\psi^c\, CD_{ir}^{\rho_i^D} + \xi^c\, CM_{ir}^{\rho_i^D}\right]^{1/\rho^D{}_i} \tag{8}$$

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

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

where Z, C, I, and G are inter-industry 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 varities in these composites is $\sigma_i^D = 1/(1-\rho_i^D)$.

The domestic imported varieties are represented by nested CES functions, and we differentiate the following structure 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:

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

where y_{itr} (y_{isr}) are imports of commodity i from region t (s) to r. π and φ are the CES share

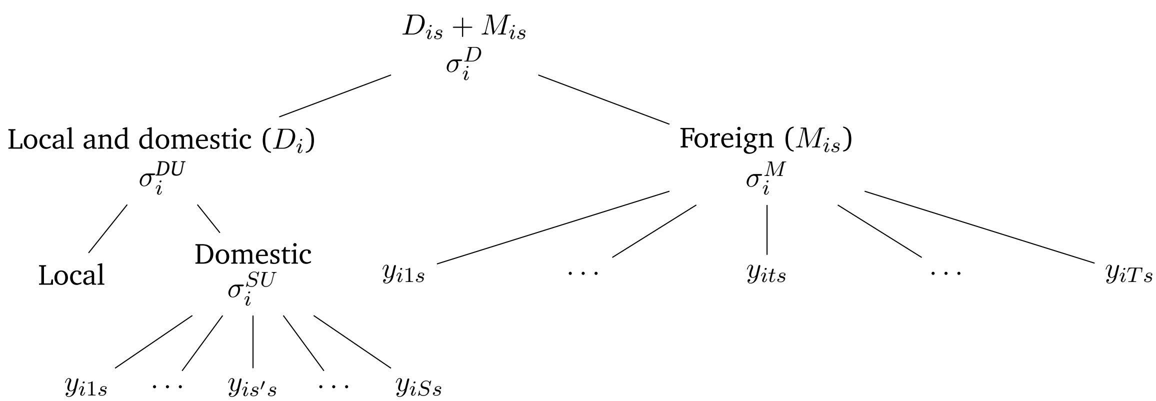

Figure 2: Aggregation of local, domestic, and foreign varieties of good i for US region s.

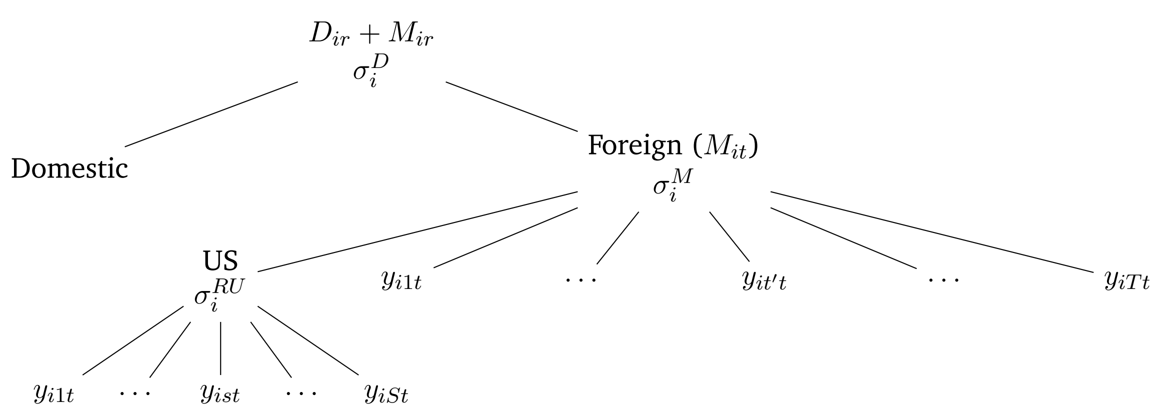

Figure 3: Aggregation of domestic and foreign varieties of good i for international region t.

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 US region s is represented by the CES aggregate:

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

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 US 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 a budget constraint that full consumption equals income:

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

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, respectively. $\overline{K}$, $\overline{VK}$, $\overline{R}$, $\overline{L}$, 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, whereas capital for international regions and labor for international and US regions are perfectly mobile across sectors within a

given region but immobile across regions. Capital in the US is assumed to be perfectly mobile across US regions but immobile across international regions. Except for labor, all factors are inelastically supplied.

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 a unit cost indexes (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 (deficit), respectively. Aggregate demand by the government is given by:

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

where p_r^G is the price for 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 must equal 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 in GAMS and use the mathematical programming system 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. Exogenous elasticities determine the free parameters of the functional forms that capture production technologies and consumer preferences. Reference values for elasticity parameters are shown in Table 3. Values for 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" that hypothesizes that the value at a given nest is twice as large as the value at the parent nest. Section 4.1 conducts 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

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:

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

The imputed returns to the exhaustible resource from this procedure 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 elasticities between the value-added composite and the sector-specific resource factor for generation from hydro and nuclear sources ($\zeta_{\text{NUC}} = 0.25$ and $\zeta_{\text{HYD}} = 0.5$).

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 Specificities of sub-national policies

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 in Anderson and van Wincoop (2003), who find trade between US states to be 2.24 times larger than trade between states and Canadian provinces. This border effect can be replicated in an Armington-type model by assuming that goods produced within the country are closer substi-

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_{hr}	Resource—Capital/labor/energy/materials in hydro 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, nuclear, and hydro resource factors are calibrated according to Eq. (18) using the following estimates for price elasticities of supply: $zeta_{\text{COL}} = \zeta_{\text{GAS}} = 1$, $\zeta_{\text{CRU}} = 0.5$, $\zeta_{\text{NUC}} = 0.25$, and $\zeta_{\text{HYD}} = 0.5$). σ_l is calibrated assuming that the compensated and uncompensated labor supply elasticity is 0.05 and 0.3, respectively.

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 US origins for international regions	$2\,\sigma_i^M$
σ_i^{DU}	Local—domestic for US regions	$2\,\sigma_i^D$
σ_i^{SU}	Across US origins for US regions	$2\,\sigma_{is}^{DU}$

tutes than goods from international sources. This is implemented in our model in a simple manner, as noted above, by setting σ_i^{DU}, the elasticity of substitution between local (within-state) and domestic goods to equal twice the value of σ_i^{D}, the elasticity of substitution between domestic and foreign goods[6]. Our model thus simulate a de-facto "border effect", and the within-country trade response will be larger than the international response. Note that, by assumption, this effect will be 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 out of the scope of the present study and is left to further research.

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). Consequently, we assume that capital is immobile between countries and perfectly mobile between US states.

Finally, as our model is intended to simulate a "medium-run" time horizon, we assume labor to be remain immobile between states as well as between countries.

3.4 Scenarios

We evaluate leakage from California's cap-and-trade program by consider five scenarios. Our first scenario, which we label "EU-ETS", simulates a cap-and-trade program in the EU. The EU-ETS aims to reduce 2020 emissions by 21% relative to 2005 emissions. The reduction in EU emissions in 2020 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, and whether or not the

[6] The sector-specific estimates of which are taken directly from GTAP

EU proceeds with plans to implement a more ambitious 2020 cap. We represent climate policy in the EU by imposing a cap that reduces EU emissions by 30% relative to benchmark emissions in our model.[7] 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 EU emissions cap is imposed in all other scenarios and changes in other simulations are expressed relative to values in the the EU-ETS scenario.

According to emissions calculations and projections by Rogers et al. (2007), the goal to reduce Californian emissions to 1990 levels is equivalent to a 29% reduction in 2020 business as usual emissions. As noted in Section 2, offsets may account for a significant proportion of the reduction in emissions, but eligible offset programs may not be able to supply the maximum quantity of offsets allowed. We take a cautious view regarding the development of offset opportunities and consider net-of-offsets cap that reduces Californian emissions by 15%. 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, Californian 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 electricity exporters respond to the tariff. If out-of-state producers can easily reconfigure transmission so that low-carbon electricity is exported to California and carbon-intensive electricity is supplied elsewhere, the tariff will have little impact on leakage. On the other hand, if electricity producers are unable to reroute supply, the policy may lead to a large reduction in leakage in states producing (on average) carbon-

[7] As we conduct a stylized analysis, we only consider CO_2 emissions and we do not consider other measures to address climate concerns, such as renewable electricity standards and low carbon fuel standards.

intensive electricity.

To bound leakage due to California's cap-and-trade program, we consider two extreme responses by electricity exporters. In one scenario, $CA^{Notariff}$, we assume that electricity exporters can avoid tariff charges by reconfiguring supply so that only carbon-free electricity is supplied to California. In another scenario, CA^{Tariff}, we calculate emissions embodied in imported electricity using emissions coefficients in exporting regions in the benchmark data. This scenario implicitly assumes that exporters do not adjust the composition of electricity due to the policy. The truth lies somewhere between these cases and work in progress attempts to calibrate realistic responses by electricity exporters.

We execute two additional scenarios to assess the impact of international trading of emission permits. One scenario, $CA\text{-}EU^{Notariff}$, allows trading of permits between the two systems without a tariff on Californian imports of electricity. The other, $CA\text{-}EU^{Tariff}$, considers trading of permits with Californian electricity tariffs.

Finally, in the EU-ETS, $CA^{Notariff}$ and CA^{Tariff} scenarios, we implement counterfactual exercises to distinguish leakage occuring via the trade channel from that occuring through the fossil fuel price channel. Leakage due to trade is estimated by holding the price of fossils fuels constant in all regions and leakage through changes in fossil fuel prices is appraised by fixing imports of all commodities except fossil fuels in all regions. As trade in factors is a substitute for trade in goods, we do not allow capital movements among regions in our decomposition analysis.[8] There are important interactions between leakage channels, so we do not expect the sum of leakage across channels in our decomposition analysis to equal leakage when all channels operate simultaneously.

[8] The restriction of inter-regional capital movements is only relevant for the US, as capital is region-specific in international regions. Also, labor is region-specific in all regions, so we do not imposes additional restrictions on labor mobility in our decomposition analysis.

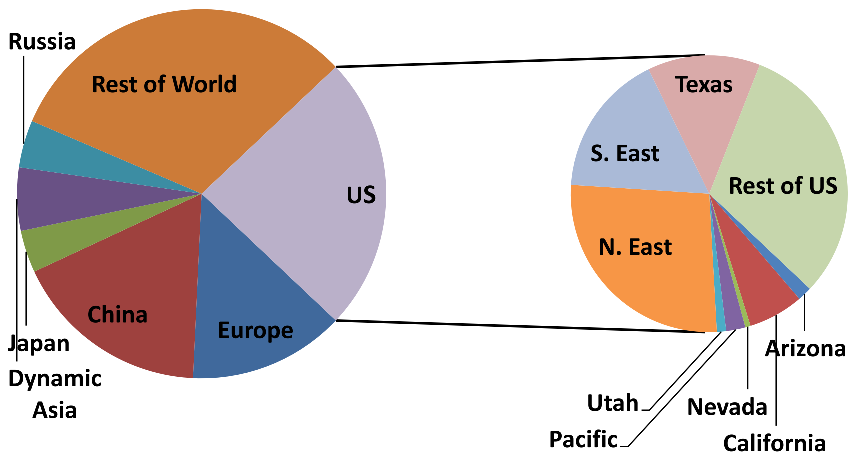

Figure 4: CO_2 emissions by region.

3.5 Descriptive analysis of the data

We describe key feature of our database before discussing our simulation results. Emissions by region are displayed in Figure 4. The US is the largest source of CO_2 emissions, and accounts for 25% of global emissions. The next largest emitters are China (18% of global emissions) and the EU (14%). Californian emissions are 5.5% of total US emissions (and 1.4% of global emissions). The largest sources of US emissions are the North East (26.9% of US emissions and 7.0% of global emissions), the South East (16.8% and 4.4%) and Texas (13.2% and 3.4%). As Californian 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.

Leakage will be influenced by the sectoral and regional composition of California's imports. Other manufacturing accounts for 36% of California's total imports, energy-intensive commodities account for 30% and electricity 2%. Most of California's imports of Other manufacturing

are from international sources such as China (22%), Dynamic Asia (19%), Mexico (10%) and Japan (9%). The North East is a significant source of energy-intensive manufacturing commodities, especially Iron and steel (45% of total imports of this commodity), Paper products (23%), Non-metallic minerals (19%), Non-ferrous metals (16%), and Chemical products (16%). Internationally, Chinese products are a relatively large share of California's imports of non-metallic minerals (10%) and chemical products (8%). Arizona (37%) is the major source for California's electricity imports, followed by Nevada (28%), the Pacific region (22%) and Utah (12%).

Electricity is a significant source of emissions in all regions. We calculate the average carbon intensity of electricity in each region by dividing the value of electricity by emissions from fossil fuels used in electricity generation. Kilograms of CO_2 from each fossil fuel per dollar of electricity production for US 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 slightly 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 total electricity production. In contrast, emissions from natural gas account for 92% of total electricity emissions in California.

CO_2 emissions embodied in imports are a function of import values and carbon intensities. Electricity accounts for one-quarter of California's total imported emissions. Around 45% of emissions embodied in imported electricity are sourced from Arizona. The corresponding shares for Utah, Nevada and the Pacific region are, respectively, 21%, 19% and 12%. Other manufacturing also accounts for a large share (29%) of imported emissions, and imports from China account for 62% of imported emissions associated with this product. Only 11% of imported Other manufacturing emissions are from other US states. Chemical products are another signif-

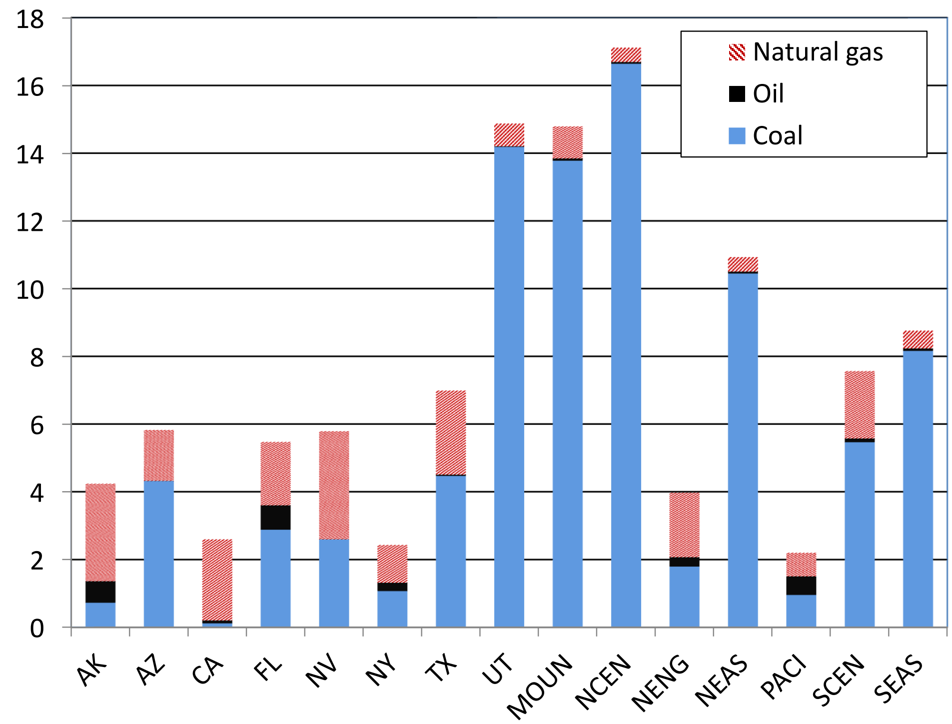

Figure 5: Kilograms of CO_2 emissions per dollar of electricity production (2004\$).

icant source of imported emissions (12%), with most emissions associated with production in China and Texas. Aggregating across regions, products sourced from US states account for 54% of total imported emissions, and the principal sources of imported emissions are China (25%), Arizona (9%) and Texas (8%).

4 Modeling results

As discussed in Section 3.4, we consider five scenarios. The EU-ETS scenario implements a cap-and-trade program in the EU and is used as a benchmark for other scenarios. Two scenarios consider a cap-and-trade program in California without international trading of permits, one with ineffective electricity tariffs, $CA^{Notariff}$, and one with effective tariffs, CA^{Tariff}. The CA-

Table 5: Emissions allowances prices, 2004$/t$CO_2$.

	EU-ETS	$CA^{Notariff}$	CA^{Tariff}	$CA\text{-}EU^{Notariff}$	$CA\text{-}EU^{Tariff}$
California	-	22.0	55.5	13.2	15.1
EU	12.5	12.5	12.5	13.2	15.1

$EU^{Notariff}$ and $CA\text{-}EU^{Tariff}$ scenarios evaluate a cap on Californian emissions allowing permit trade between California and the EU, respectively, without and with effective electricity tariffs.

Results are summarized in Tables 5 to 7. CO_2 allowance prices, in 2004 dollars, are displayed in Table 5, and Table 6 presents leakage rates to each region. Table 6 also displays aggregate leakage to regions that export electricity to California (Arizona, Nevada, Utah and the Pacific region), and other US and international (non-US) regions. Leakage to each region is calculated as the increase in emissions in that region divided by the decrease in emissions mandated by the EU-ETS in the EU-ETS scenario and by California's cap-and-trade program in other scenarios.[9]

Leakage depends on the extent to which the policy induces increased production of energy-intensive goods, especially electricity, outside of California, and how changes in fossil fuel prices affect energy use in other regions. 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 7. The table also reports aggregate leakage (i) summed across the two sources and (ii) simulated when both channels operate simultaneously (as reported in Table 6).

CORRECTED : - EU PRICE (WAS 20, SHOULD BE 12.5?)

In the EU-ETS scenario, the allowance price is \$12.5 per metric ton of CO_2 (tCO_2) and the leakage rate to all regions is 19% of the reduction in EU emissions. The largest sources of

[9] Leakage is commonly defined as the increase in emissions in non-constrained regions divided by the decrease in emissions in constrained regions. Our calculation is equivalent to this definition in scenarios without electricity tariffs. When allowances are required for imported electricity, fewer allowances are available for domestic use and there is a smaller denominator in our leakage formula than in conventional leakage calculations.

Table 6: Leakage rates, %.

	EU-ETS	$CA^{Notariff}$	CA^{Tariff}	$CA\text{-}EU^{Notariff}$	$CA\text{-}EU^{Tariff}$
AK	0.1	0.5	0.9	0.3	0.4
AZ	0.0	18.6	-41.7	11.7	-21.4
FL	0.0	2.0	2.8	1.3	1.1
NV	0.0	5.2	0.6	3.3	2.3
NY	0.0	0.7	0.9	0.6	0.6
TX	0.4	11.1	19.4	6.5	5.9
UT	0.0	12.1	-23.9	6.9	-17.8
MOUN	0.2	1.1	10.2	0.9	4.6
NCEN	0.1	-4.7	-5.0	-3.1	-1.6
NENG	0.0	0.3	1.2	0.3	0.5
NEAS	0.1	-5.7	12.3	-3.6	7.4
PACI	0.0	4.9	6.2	2.9	4.3
SCEN	0.0	0.2	1.0	0.0	0.2
SEAS	0.7	-0.2	14.1	-0.1	3.1
AFR	3.2	0.1	0.5	1.1	4.2
ANZ	0.7	0.0	0.1	0.2	0.8
ASI	1.6	0.2	1.2	0.5	2.0
BRA	0.2	0.0	0.2	0.1	0.3
CAN	0.8	1.0	-0.3	0.9	1.0
CHN	3.1	0.0	0.6	0.9	3.7
IND	0.9	0.0	0.3	0.2	1.1
JPN	0.8	0.1	0.6	0.3	1.1
LAM	0.7	-0.1	0.2	0.1	0.9
MES	0.5	0.2	0.8	0.2	0.8
MEX	0.1	-0.1	0.1	-0.1	0.0
REA	0.3	0.0	0.1	0.1	0.3
ROE	2.1	-0.1	0.5	0.5	2.5
RUS	2.1	0.0	0.8	0.6	2.6
Elec. Exporters	0.0	40.8	-58.8	24.8	-32.7
Rest of US	1.7	5.1	57.8	3.2	22.2
US	1.7	45.9	-1.0	27.9	-10.5
International	17.1	1.5	5.9	5.7	21.3
All regions	18.8	47.4	4.9	33.6	10.8

Note: "Electricity exporters" references regions that export electricity to the California (Arizona, Nevada, Utah and the Pacific region).

Table 7: Leakage due to fossil fuel price and trade channels.

	EU-ETS	$CA^{Notariff}$	CA^{Tariff}
Fossil fuel prices:			
Elec. exporters	0.1	16.0	15.7
Rest of US	1.2	2.2	14.5
International	15.7	-7.9	16.4
All regions	17.0	10.3	49.7
Trade:			
Elec. exporters	0.0	40.4	-65.2
Rest of US	0.8	3.9	14.1
International	5.7	5.4	5.4
All regions	6.5	49.7	-45.7
All channels (summation):			
Elec. exporters	0.1	56.4	-49.4
Rest of US	2.1	6.1	28.6
International	21.4	-2.5	21.8
All regions	23.5	59.9	4.0
All channels (simulated):			
Elec. exporters	0.0	40.8	-58.8
Rest of US	1.7	5.1	57.8
International	17.1	1.5	5.9
All regions	18.8	47.4	4.9

leakage are Africa and China. Leakage rates to all regions are positive. US emissions increase by 2% of the reduction in EU emissions. Table 7 indicates that a large proportion of leakage occurs via the fossil fuel price channel. 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. There is also leakage via the trade channel, mainly due to increased EU imports of Electricity, Iron and steel, and Metals nec.

In the $CA^{Notariff}$ scenario, the Californian allowance price is \$22/tCO_2. The allowance price reduces Californian electricity production by 21% and there is a large decrease in the demand for natural gas. A large proportion of the reduction in Californian electricity production is replaced by imported electricity, which results in leakage to electricity exporters. The largest leakage sources are Arizona (19%), which experiences the largest increase in electricity exports

to California, and Utah (12%), 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 US regions. In regions with a high proportion of electricity generated from coal, such as North Central and North East, the price changes reduce emissions from electricity. The largest negative leakage rate (-6%) is observed for the North East, however the proportional change in North East emissions is 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 (11%) is due to increased in Chemical, rubber and plastic products exports to California. In aggregate, leakage to electricity exporters is 41% and leakage to other US regions is 5%. There is only a small amount of leakage to international sources (2%). Due to a large increase in Californian electricity imports, most leakage occurs via the trade channel.

When the Californian tariff on imported electricity is effective, (CA^{Tariff}), the allowance price is $55/t$CO_2$. This is much higher than in the $CA^{Notariff}$ scenario, as the electricity tariff restricts a low cost abatement option for California, and because allowances surrendered for imported electricity reduces the quantity of allowances that can be used for in-state production. The policy increases Californian consumption of electricity generated in California and the Pacific region at the expensive of carbon-intensive electricity from Arizona and Utah. As a result, there is positive leakage to the Pacific region (6%) and negative leakage to Arizona (-42%) and Utah (-24%).

Leakage to other regions is driven by changes in fossil fuel prices. In California, there are two competing effects on the natural gas price: (i) pricing emissions induces a substitution away

from natural gas and (ii) the electricity tariff increases demand for natural gas. The second effect dominates in our analysis. There is also decreased demand for refined oil in California and for coal in regions exporting electricity to California. These demand changes decrease the composite fossil fuel price and increase the price of natural gas relative to coal. Ultimately, these changes increase emissions in other regions, mainly due to their impact on electricity and transportation. As in the $\text{CA}^{\text{Notariff}}$ scenario, there is also leakage associated with increased Chemical and rubber and plastic products in Texas. The leakage rate to US regions that do not export electricity to the US is 58%, but there is negative leakage within the US due to large decreases in emissions in Arizona and Utah. Leakage to international regions is 6% and mainly occurs through the fossil fuel price channel. The leakage rate to all regions is 5%, which is substantially lower than in the $\text{CA}^{\text{Notariff}}$ scenario.

International trading of emissions permits equalizes permit prices across the two systems. As the EU market for emissions permits is three times the size of that in California, the common permit price is close to the EU autarky price. In the $\text{CA-EU}^{\text{Notariff}}$ scenario, the lower permit price relative to the corresponding case without permit trading decreases leakage to US regions (from 46% in the $\text{CA}^{\text{Notariff}}$ scenario without international permit trading to 28% in the $\text{CA}^{\text{Notariff}}$ scenario with international permit trading). Most of this decrease is due to decreased Californian electricity imports. International permit trading increases emissions to international sources, which is driven by the increase in the permit price in the EU.

In the case where the California electricity tariff is effective, international permit trading decreases the tariff on imported electricity and, in a relative sense, increases leakage to electricity exporters (from -59% in the $\text{CA}^{\text{Tariff}}$ scenario to -33% in the $\text{CA-EU}^{\text{Tariff}}$ scenario). There is a reduction in leakage to other US regions, as the lower permit price in California reduces fossil fuel price changes observed in the $\text{CA}^{\text{Tariff}}$ scenario. The net impact is a decrease in leakage to US

regions to -11% (i.e., an increase in negative leakage). Compared to when the electricity tariff is not effective, there is a large increase in international leakage due to the higher permit price in the EU. Overall, contrary to the case when out-of-state generators can avoid the electricity tariff, trading of international permits increases leakage when the electricity tariff is effective.

4.1 Sensitivity analysis

A key driver of our results is that changes in California have larger impacts on US regions than international regions. Accordingly, we consider "Low" and "High" alternative values for elasticities governing substitutability in US demand between domestic and imported production (σ_i^{DU}), and among imports from US 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 Californian goods than goods from other states. In high variant cases, we double base values for σ_i^{DU} and σ_i^{SU}.

Leakage rates for aggregated regions in the $\text{CA}^{\text{Notariff}}$ and $\text{CA}^{\text{Tariff}}$ scenarios are presented in Table 8. The first component of case labels convey values for σ_i^{DU} and the second component communicates values for σ_i^{SU}. By design, the first column of results replicate leakage rates in Table 6. Decreasing σ_i^{DU} reduces substitution in California electricity demand away from imported electricity, so there is less leakage to electricity exporters in the the Low-Base case than in our core (Base-Base) scenario. Changing the value of σ_i^{SU} has only a minor impact on leakage as changes in relative prices of imported electricity across sources are small. Increasing σ_i^{DU} results in more substitution towards imported electricity and greater leakage.

In the $\text{CA}^{\text{Tariff}}$ scenario, there is less negative leakage to electricity exporters in the Low-

Table 8: Leakage rates for alternative Armington elasticity values, %.

	σ_i^{DU} — σ_i^{SU}				
	Base-Base	Low-Base	Base-Low	Low-Low	High-High
$CA^{Notariff}$:					
Elec. exporters	40.8	23.3	39.8	23.6	65.0
Rest of US	5.1	10.9	0.8	7.7	3.9
International	1.5	2.4	1.8	2.8	-0.2
All regions	47.4	36.7	42.5	34.0	68.7
CA^{Tariff}:					
Elec. exporters	-58.8	-54.1	-55.4	-49.5	-61.6
Rest of US	57.8	56.7	60.4	59.0	57.4
International	5.9	7.1	7.1	8.8	3.1
All regions	4.9	9.7	12.2	18.3	-1.2

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

Base, Base-Low and Low-Low cases than in our core scenario as there is less scope for California to substitute away from electricity imports and, within the imported electricity composite, less substitution possibilities away from more carbon-intensive sources. The opposite is true in the High-High case, which results in negative leakage to electricity exporters of -62%. Overall, the analysis indicates that our findings are relatively insensitive to our specification of elasticities for US imports and model responses are mostly determined by initial trade shares.

5 Conclusions

This paper considered leakage from sub-national climate policies using California's cap-and-trade program as a representative example. Our analysis employed a global model of economic activity and energy systems that identified 15 US regions and 15 regions in the rest of the world. The framework explicitly modeled bilateral trade flows among all regions.

A key feature of California's cap-and-trade policy is that allowances must be surrendered for

emissions embodied in imported electricity, which is analogous to an import tariff. The effectiveness of this measure will depend on the ability of out-of-state generators to lower the incidence of the tariff by rerouting electricity transmission so that less carbon-intensive electricity is supplied to California. To bound leakage resulting from California's cap-and-trade program, we considered two contrasting situations. In one case, the electricity tariff was ineffective, as electricity exporters could costlessly reconfigure supply so that carbon-free electricity is supplied to California and carbon-intensive electricity was transmitted elsewhere. In the other, out-of-state generators were unable to adjust the composition of electricity supply in response to the tariff.

We observed significant leakage via the trade channel due to changes in California's imports of electricity. When the electricity tariff was ineffective, there was a large substitution in California towards imported electricity. This resulted in leakage to regions exporting electricity to California of 41% of the decrease in emissions in California. Leakage to other regions occurred mainly through changes in fossil fuel prices. As natural gas-fired electricity accounts for a large share of electricity production in California and generation from coal is a high proportion of total generation in regions that export electricity California, the policy decreased the price of natural gas and increased the price of coal. These price changes increased emissions in regions producing a large proportion of electricity from natural gas, and decreased emissions in regions reliant on coal-fired electricity. Aggregate leakage when electricity tariffs were ineffective was 48%.

Leakage rates differed substantially when out-of-state generators could not reroute electricity supply to avoid the tariff. In this case, as electricity imported by California is relative carbon intensive, the policy decreased the relative price of in-state electricity in California and resulted in negative leakage to electricity exporters. These changes decreased the relative price of coal and ultimately increased leakage to other regions. Aggregate leakage was 5% when electricity

tariffs were effective.

We also considered leakage when there was trading of emissions permits between California and the EU-ETS. As California's autarky allowance price was higher than that in the EU, international permit trading reduced the cost of allowances in California. When electricity tariffs were ineffective, the lower permit price reduced substitution towards imported electricity and aggregate leakage decreased relative to a case without international permit trading. Permit trading lowered the incidence of electricity tariffs when tariffs were effective, which reduced negative leakage to regions exporting electricity to California. Smaller changes in electricity production in regions supplying California dampened down changes in US fossil fuel prices and decreased leakage to other US regions. In aggregate, international permit trading increased leakage when electricity tariffs were effective. The large variance in leakage rates across scenarios suggests that future research should focus on the ability of out-of-state generators to alter the composition of electricity exported to California.

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Appendix: Structure of Production and Consumption Technologies

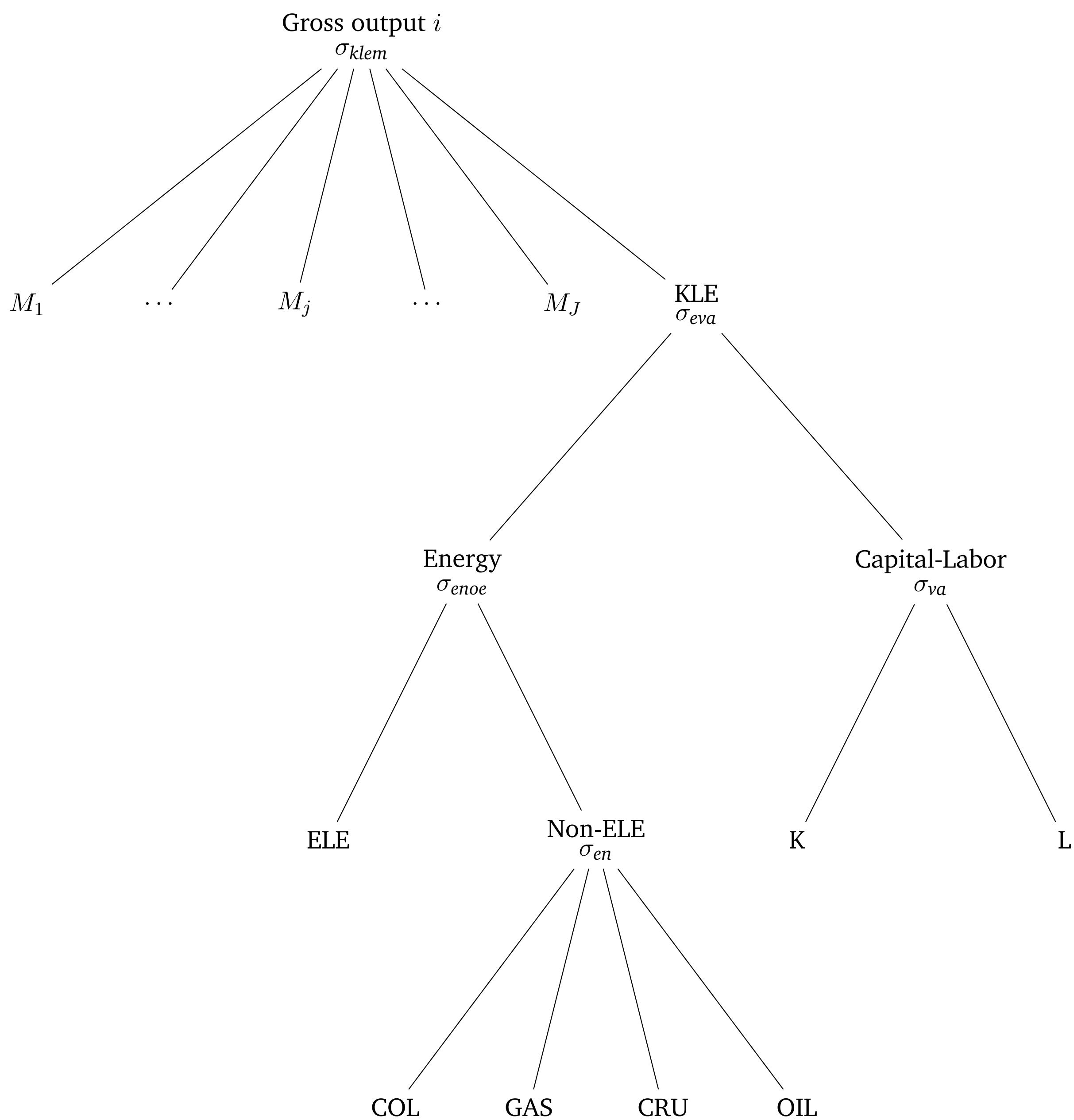

Figure A 1: Structure of production for $i \in$ {TRN,EIS,SRV,CRP,I_S,NFM,NMM,PPP,MAN}.

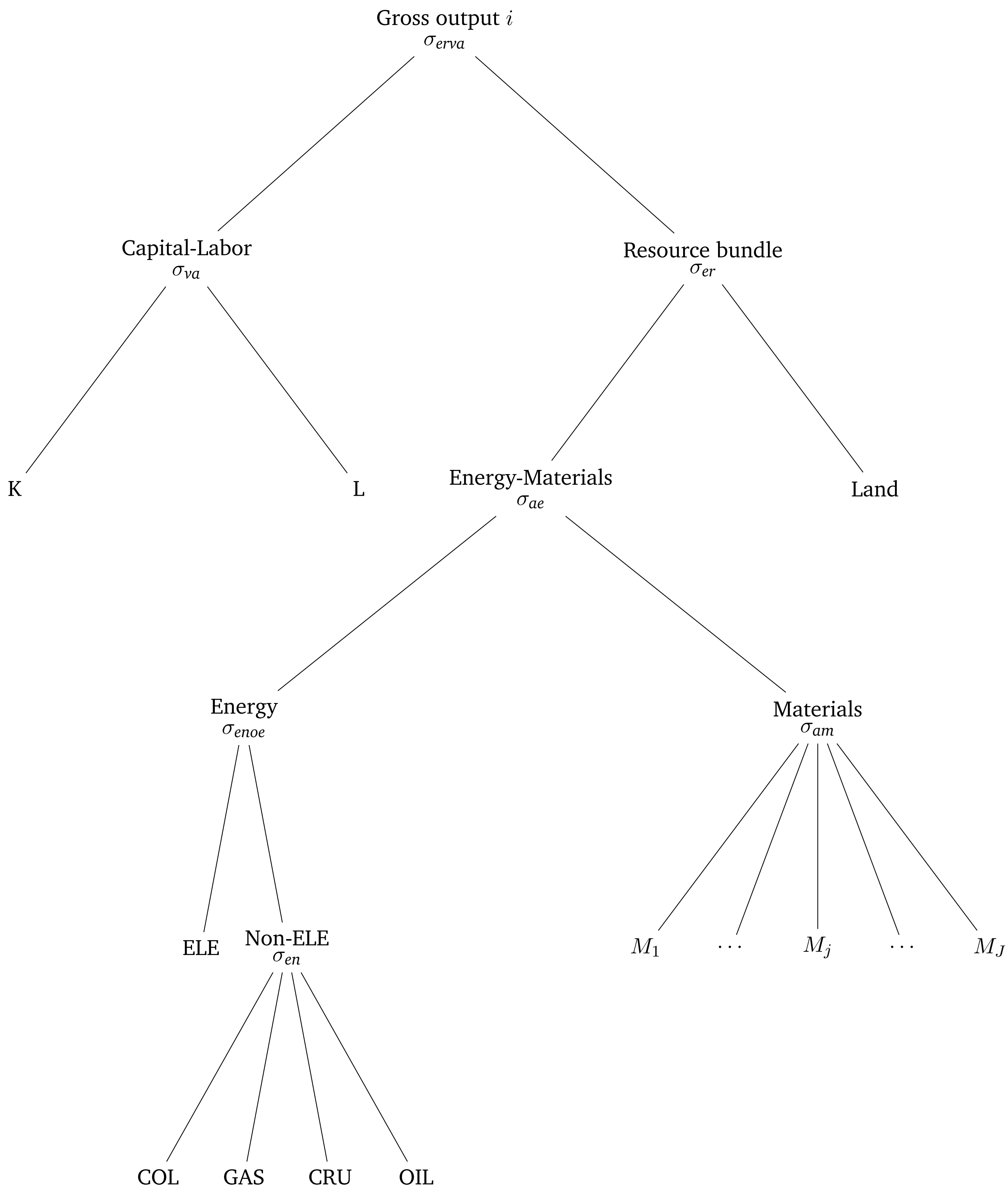

Figure A 2: Structure of production for $i \in$ {AGR}.

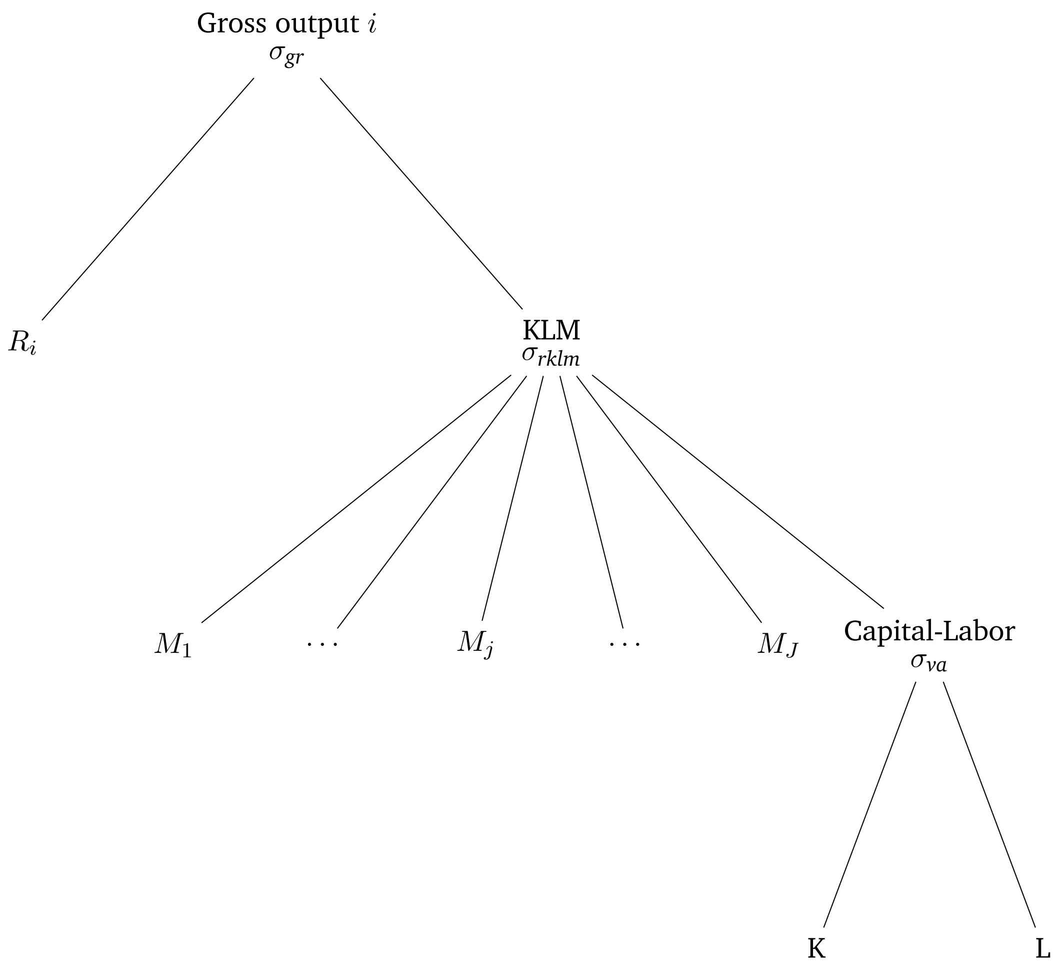

Figure A 3: Structure of primary energy sectors $i \in$ {COL,CRU,GAS}.

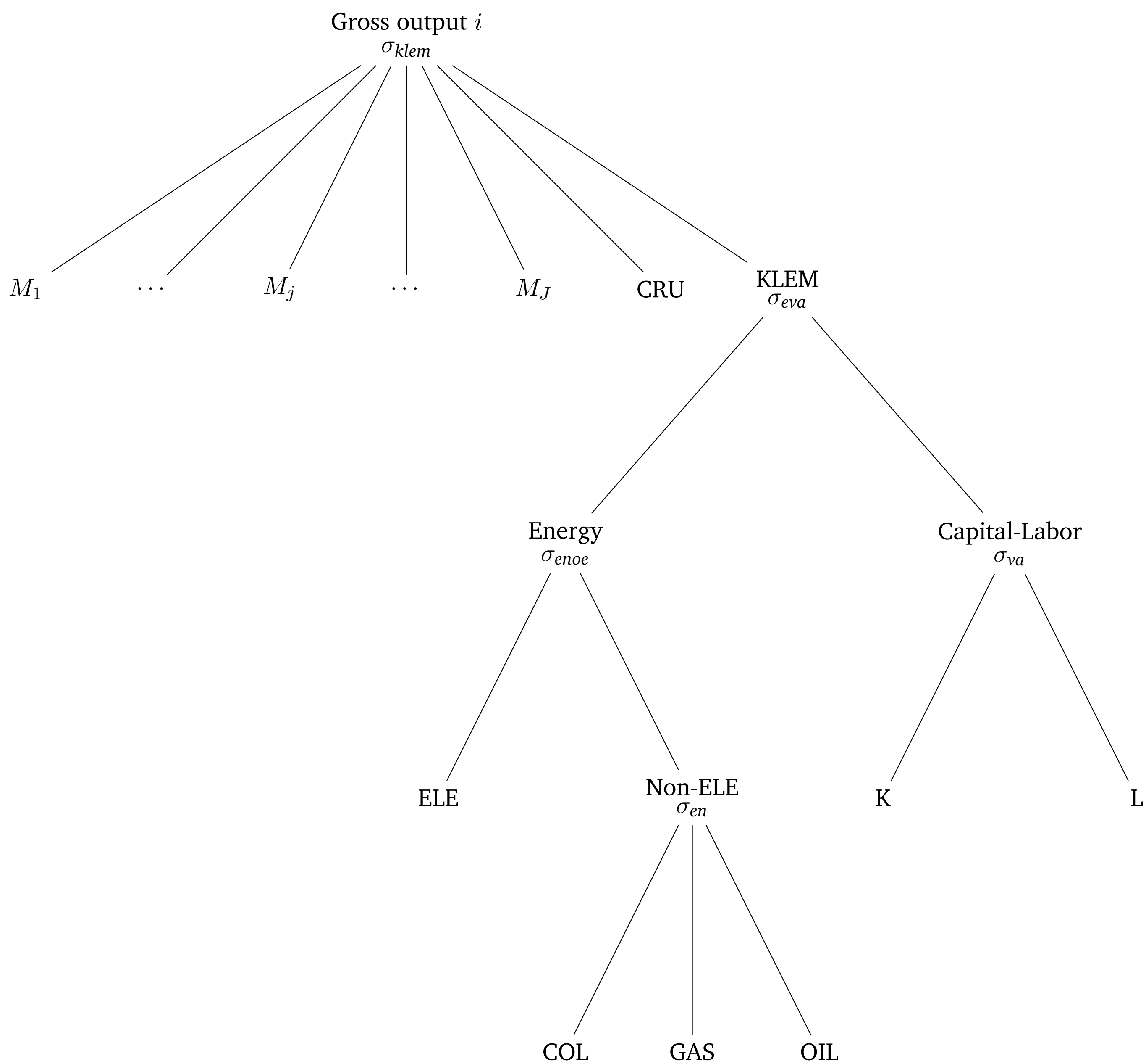

Figure A 4: Structure of production for $i \in \{\text{OIL}\}$.

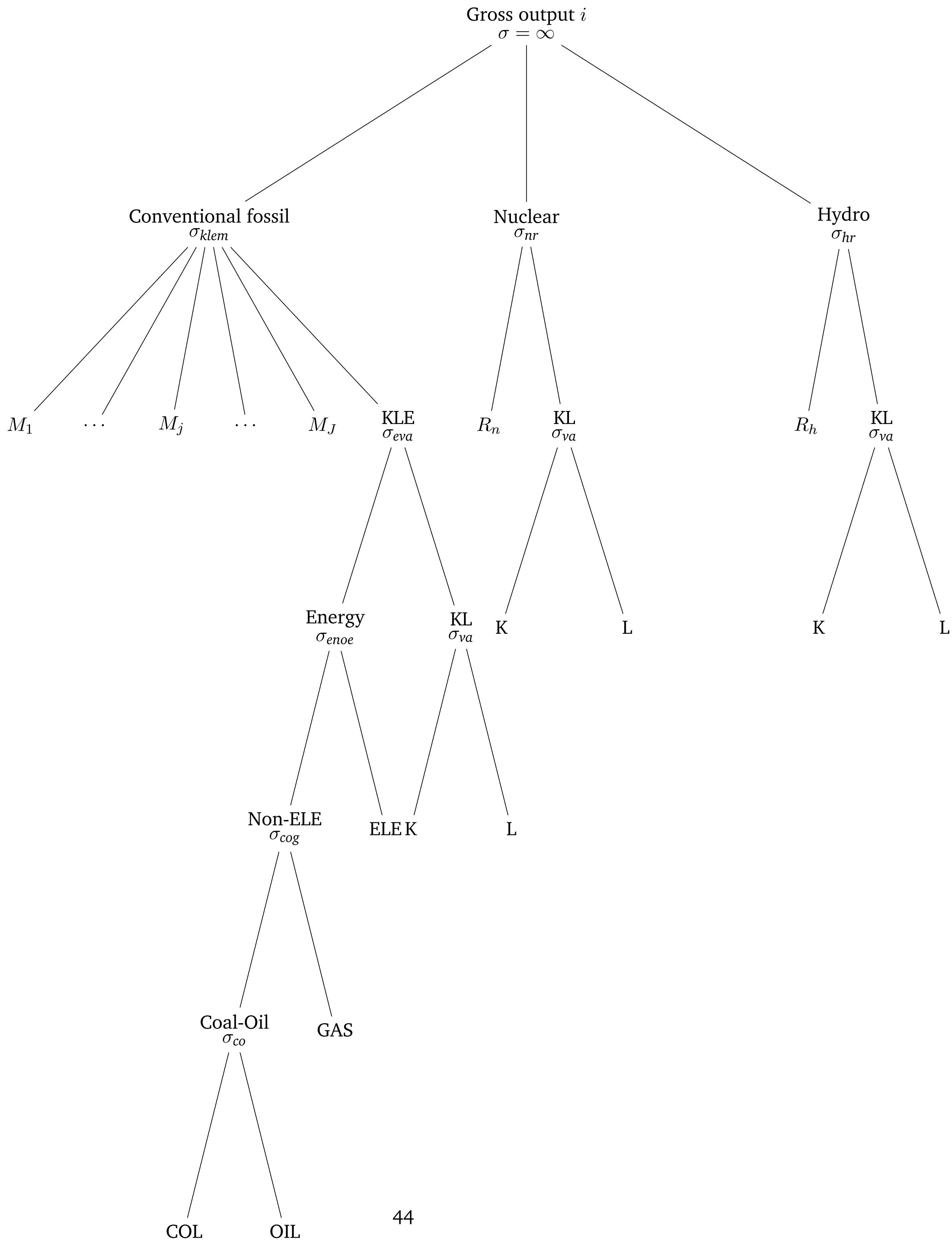

Figure A 5: Structure of electricity production $i \in \{\text{ELE}\}$.

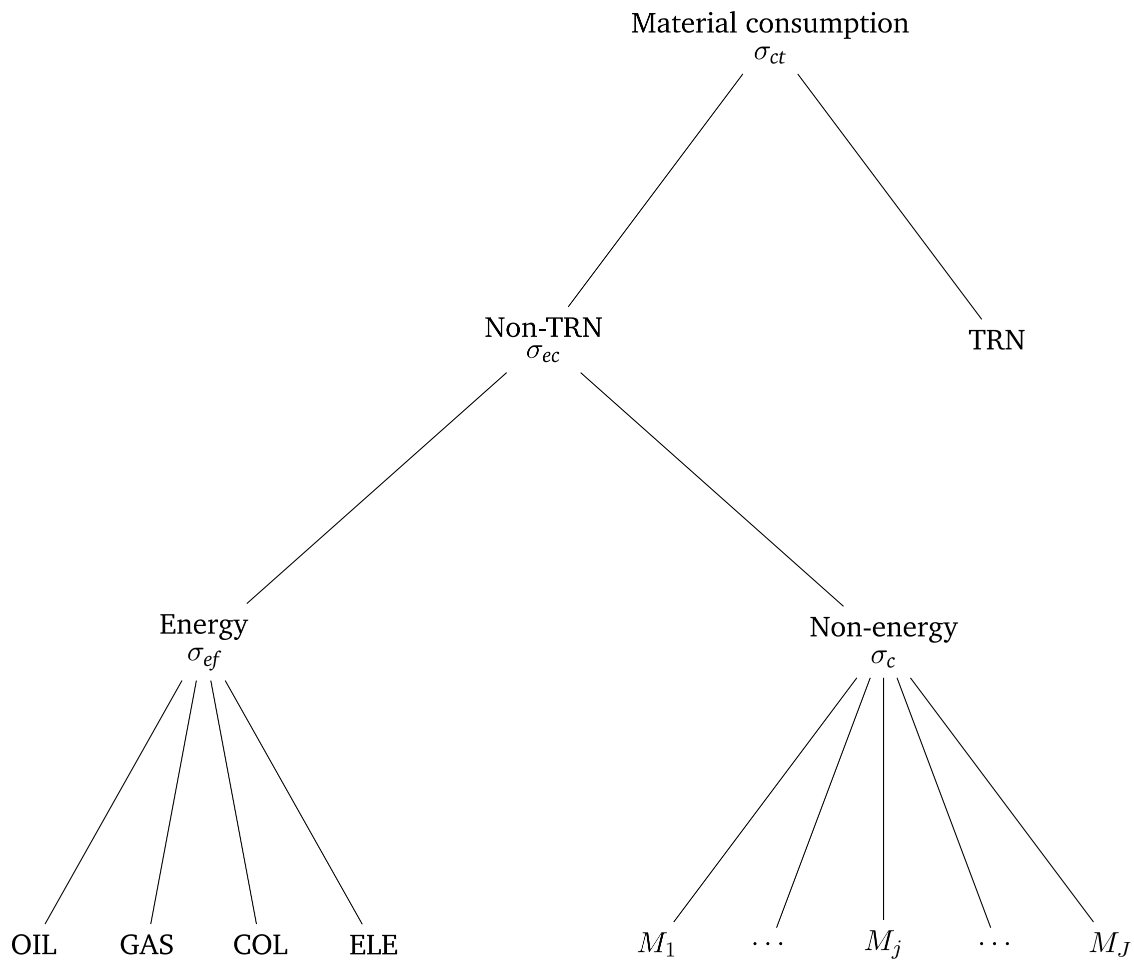

Figure A 6: Structure of private material consumption.