Leakage from sub-national climate initiatives: The case of California*

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Abstract

With federal policies to curb carbon emissions stagnating in the US, California is taking action alone. Sub-national policies can lead to high rates of emissions leakage to other regions as state-level economies are closely connected, including integration of electricity markets. Using a calibrated general equilibrium model, we estimate that California's cap-and-trade program without restrictions on imported electricity increases out-of-state emissions by 46% of the domestic reduction. When imported electricity is included in the cap and "resource shuffling" is banned, as set out in California's legislation, emissions reductions in electricity exporting states compensate for leakage elsewhere and overall leakage is 2%.

Keywords: Leakage, sub-national climate policy, tradable permits, embodied emissions, computable general equilibrium modeling.
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1 Introduction

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Leakage occurs when greenhouse gas (GHG) restrictions in some regions increase emissions elsewhere. Climate policies can cause leakage via their impacts on trade, fossil fuel 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, Karney and Baylis, 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 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 US states to be 2.24 times larger than trade between states and Canadian provinces.

With federal initiatives to curb GHGs stalling in the US, sub-national polices have received greater focus. To date, two regional 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 emission 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 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 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 allowing trading of permits between Californian 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; Bernstein et al., 1999; Babiker and Rutherford, 2005; 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. 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 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. The CARB's finalized details of a cap-and-trade program October 20, 2011 and the legislation was approved by the California Office of Administrative

Law on December 13, 2011.

The legislation covers emissions of major GHG gases, including carbon dioxide (CO_2). 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 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 the Californian 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 third parties outside of California, 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 an 85% of California's GHG emissions, including emissions from transportation fuels, natural gas and other fuels. The legislation allows limited use of approved offset credits in lieu of allowances. Economic analysis by the CARB indicates that 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).

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.[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, 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.

[1] Current WCI 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.

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 (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 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 (SAMs) 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

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)

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 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, 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 the National Renewable Energy Laboratory's ReEDS model (Short et al., 2009). The ReEDS model simulates electricity flows between

[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.

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 optimization 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. Primary factors in the dataset include labor, capital, and

[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.

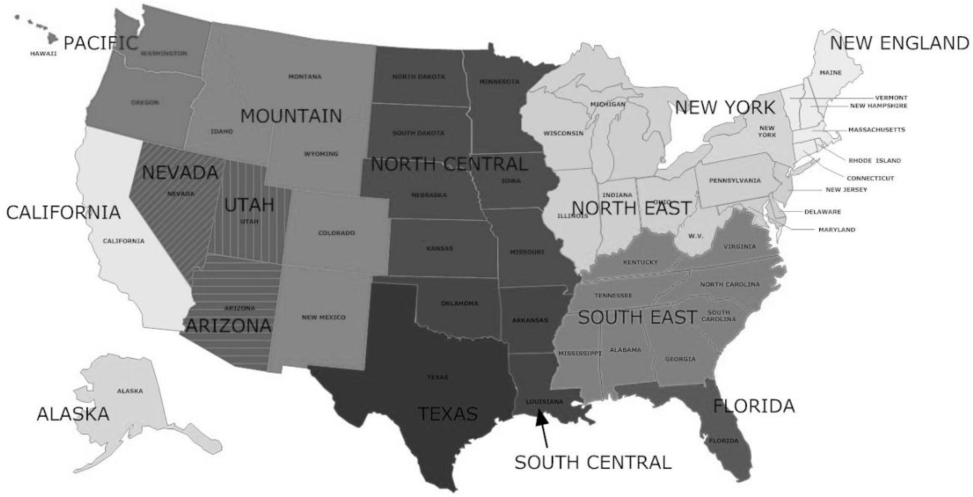

Figure 1: Aggregated regions for the US.

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.

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 ($i = 1, \ldots, I$, $i = j$) 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]

[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.

Table 2: Model aggregation.

US regions	International regions	Commodities
New England	Russia	Agriculture
New York	China	Coal mining
South East	India	Natural gas extraction
North East	Japan	Crude oil
Florida	Rest of Americas	Electricity
South Central	Rest of Europe and Central Asia	Refined oil
North Central	Dynamic Asia	Transportation
Texas	Rest of East Asia	Chemical, rubber, plastic products
Mountain	Australia and Oceania	Ferrous metals
Pacific	Middle East	Metals
California	Africa	Non-metallic minerals
Alaska	Europe	Paper products, publishing
Nevada	Canada	Leather and wood products
Utah	Mexico	Other energy-intensive industries
Arizona	Brazil	Manufacturing
		Services

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

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); refined oil, electricity, agriculture, and non-energy industries (indexed by n). All industries are characterized by constant returns to scale (except for fossil fuels, agriculture and renewable electricity, which are produced subject to decreasing returns to scale) and are traded in perfectly competitive markets.

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 function of labor and capital: $V_{fr} = L_{fr}^{\beta_{fr}} K_{fr}^{1-\beta_{fr}}$

where β is the labor share.

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

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

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):

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

where μ and γ are CES share coefficients, $g(\cdot)$ is a CES composite of energy and non-energy goods, and the elasticity of substitution between leisure and the consumption-investment composite is given by $\sigma_{l,r} = 1/(1-\rho_{cr})$.

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:

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

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

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

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

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 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 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:

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

where y_{itr} (y_{isr}) are imports of commodity i from region t (s) to r. π and φ are the CES share coefficients, and $\sigma_i^M = 1/(1-\rho_i^M)$ and $\sigma_i^{RU} = 1/(1-\rho_i^{RU})$ are the implied substitution elasticity across foreign and intra-US origins, respectively. The domestic variety of good i for US region s is represented by the CES aggregate:

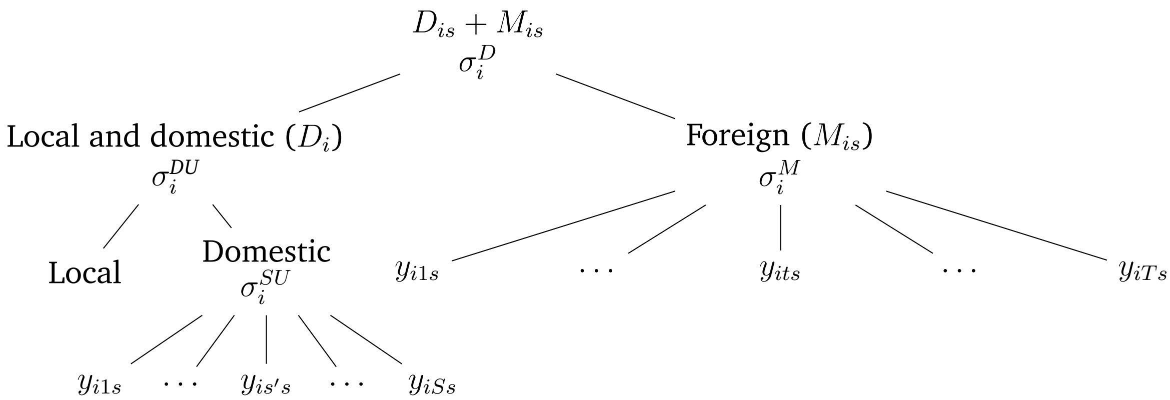

Figure 2: Aggregation of local, domestic, and foreign varieties of good i for US region s.

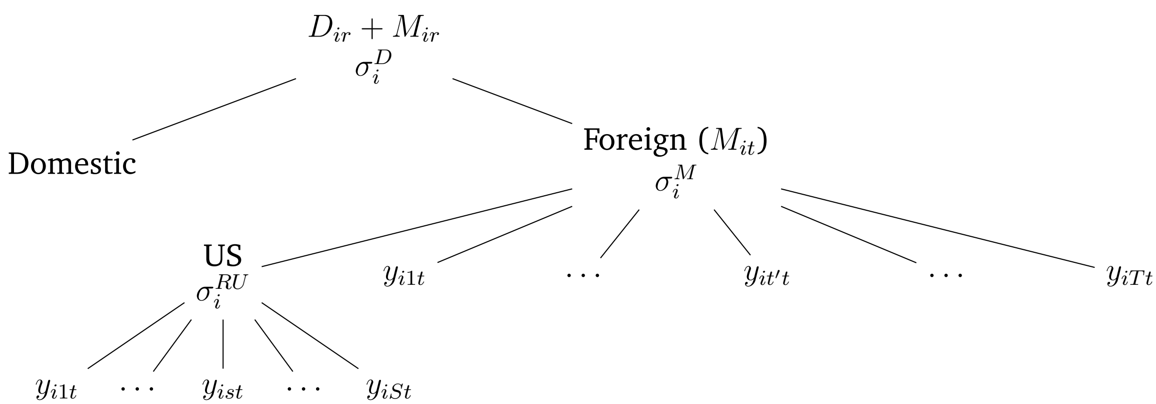

Figure 3: Aggregation of domestic and foreign varieties of good i for international region t.

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

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

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 consumption equals income:

$$\max_{\{C_{ir},I_r,N_r\}} U_r \ s.t. \ p_r^i I_r + p_r^l N + \sum_i p_{ir}^c C_{ir} = p_r^k \overline{K}_r + p_r^{Vk} \overline{VK}_r + p_{fr}^R \overline{R}_{fr} + p_r^l \overline{L}_r + T_r \tag{10}$$

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

Given input prices gross of taxes, firms maximize profits subject to the technology constraints Minimizing input costs 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: $GD_r = GOV_r/p_r^G$ 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 clearing equations are: (1) Supply to the domestic market equals demand by industry, household, investment, and government, (2) import supply of good i satisfies domestic demand by industry, household, investment, and government for the imported variety, (3) trade between all regions in each commodity is balanced, and (4) labor supply equals labor demand.

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. 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 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. That is, we set the elasticity of substitution between local (within-state) and domestic 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. Section 4.5 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 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:

$$\zeta_f = \sigma_{fr}^{R} \frac{1-\alpha_{fr}}{\alpha_{fr}} \,. \tag{11}$$

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 elasticity between the value-added composite and the sector-specific resource factor for generation from nuclear sources ($\zeta_{\text{NUC}} = 0.25$). We set $\zeta_{\text{NUC}} = 0$ for all US regions reflecting our assumption that nuclear cannot expand above current levels, which we believe is consistent with current political realities and with the 10-year horizon of our analysis.

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

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*
σ_i^D	Foreign—domestic (and local)	GTAP, version 7
σ_i^M	Across foreign origins	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	$2\,\sigma_{is}^{DU}$

Note: Substitution elasticity for fossil fuel, and nuclear resource factors are calibrated according to Eq. (11) 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.

The supply response of our renewable electricity is calibrated by setting ζ_{RNW} equal to the generation-weighted average of own-price supply elasticities for hydro and renewable electricity, where weights for generation by source are derived from EIA (2009). Following Paltsev et al. (2005) 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 region exporting to California, the CO_2 intensity of output, the share of California's imports of embodied CO_2 emissions attributable to that region, and total CO_2 emissions (represented by bubble size). In aggregate, US regions account for 23% of global CO_2 emissions. The next largest emitters are China (17%) and the EU (14%). Californian emissions (not shown in Figure 4) are 5.5% of total US emissions (and 2% of global emissions). The largest sources of US emissions are the North East (27% of US emissions and 6% of global emissions), the South East (17% and 4%) and Texas (13% and 3%). 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.

China accounts for the largest share of emissions embodied in California's imports, followed by Arizona and Texas. Electricity accounts for one-quarter of California's total imported emissions, mostly from Arizona (45%) Utah (21%), and Nevada (19%). Other major sources of imported emissions include Other manufacturing from China; and 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 US regions are displayed in Figure 5. Compared

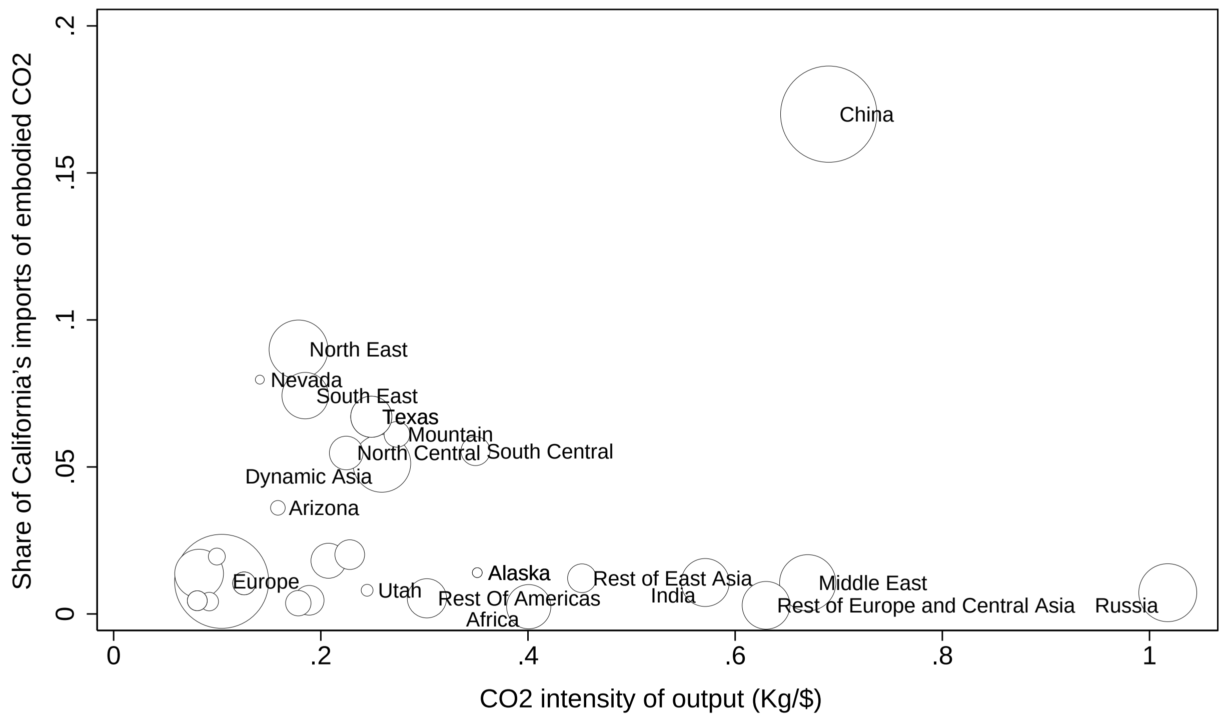

Figure 4: Scatter plot of share of California's imports of embodied carbon and carbon intensity of trading partner. Size of bubbles denotes benchmark CO_2 emissions.

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 total electricity production. In contrast, emissions from natural gas account for 92% of total electricity emissions in California.

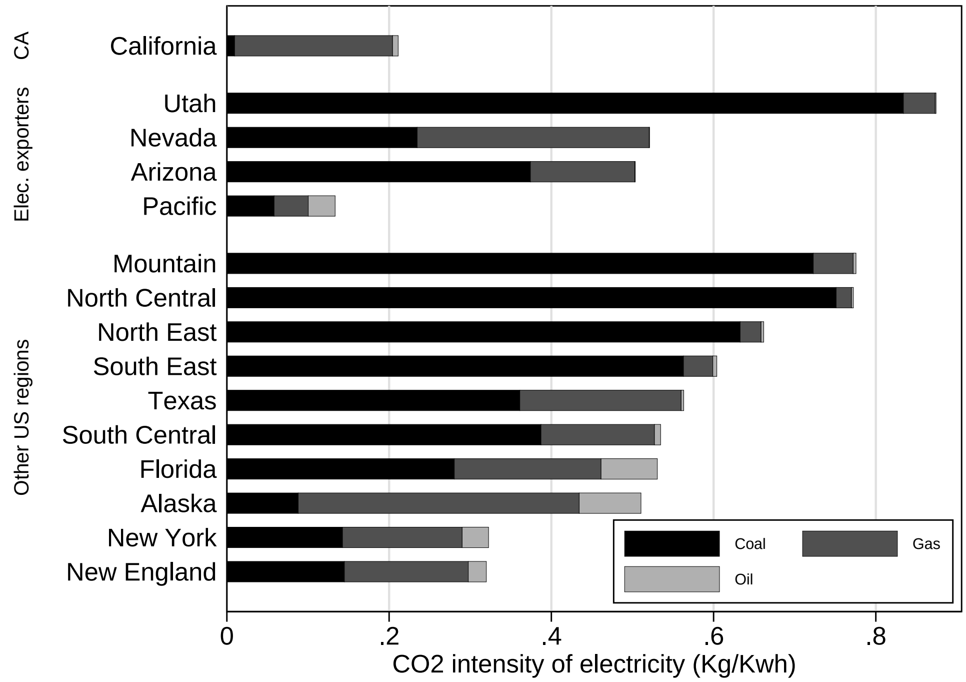

Figure 5: Kilograms of CO_2 emissions per dollar of electricity production.

4 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. The EU-ETS aims to reduce 2020 emissions by 21% relative to 2005 emissions. The 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 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 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.

The reduction in California 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.[7] 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, 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 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 re-

[7] 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.

duction 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 our $\text{CA}^{\text{noTariff}}$ scenario, we consider a cap on Californian 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 emissions coefficients in exporting regions in 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 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 Californian imports of electricity. The other, $\text{CA-TRD}^{\text{noShuffling}}$, considers trading of permits with Californian electricity tariffs and no resource shuffling.

Finally, in the EU-ETS, $\text{CA}^{\text{noTariff}}$ and $\text{CA}^{\text{noShuffling}}$ scenarios, we implement a counterfactual exercise to distinguish 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 fossils 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.[8]

4.2 Leakage without electricity tariffs

Modeling results are summarized in Tables 4 to 7. CO_2 allowance prices, in 2004 dollars, are displayed in Table 4, as well as a summary of emissions reductions and leakage rates for leakage (i) to US 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 emissions in the EU-ETS in the EU-ETS scenario, and the decrease in emissions in California in scenarios that consider California's cap-and-trade program. In our scenarios that consider electricity tariffs, the reduction in Californian emissions depends on quantity of permits used for imported electricity. Consequently, the denominator for leakage calculations varies across scenarios that consider

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

Table 4: Summary of results

Scenario name	EU-ETS	$CA^{noTariff}$	$CA^{Shuffling}$	$CA^{noShuffling}$	$CA\text{-}TRD^{noTariff}$	$CA\text{-}TRD^{noShuffling}$
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

California's cap-and-trade program.

Table 5 disaggregates leakage rates by region for each scenario and Table 6 disaggregates leakage amoung sectors for the $CA^{noShuffling}$ 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 7. By design the last panel of Table 7 replicates aggregate results reported in Table 5.

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. US emissions increase by 2% of the reduction in EU emissions. Table 7 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

	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
International regions	19.0	-6.2	-0.6	6.9	-8.0	46.0
All regions	20.5	46.3	48.1	1.5	46.7	40.4

Table 5: Leakage rates in % (based on domestic reduction)

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, the Californian allowance price is \$12/tCO_2. The allowance price reduces Californian electricity production by 21% and there is a 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 (24%), which experiences the largest increase in electricity exports to 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 US regions. In regions with a high propor-

Table 6: 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

tion of electricity generated from coal, the 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 US, leakage to electricity exporters is 53% and leakage to other regions is -1%. Leakage to international regions is is -6%, as positive leakage via the trade channel is more than offset by negative leakage due to changes in fossil fuel prices.

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

Table 7: 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

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.

4.3 The impact of electricity tariffs

Tariffs with resource shuffling. When there are tariffs on imported electricity but no resource shuffling provisions, $CA^{Shuffling}$, 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 the CO_2-intensity of electricity exports by 50%. As a result, relative to the $CA^{noTariff}$ scenario, Nevada and Utah export less electricity to California (and leakage to these regions decrease) and Arizona and the Pacific region export more (and leakage to these regions increase). Total leakage to electricity exporters decreases to 38% (from 54% in the $CA^{noTariff}$ scenario). Leakage to other US 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.

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 \$65/tCO_2 and, due to the use of permits for imported electricity, the reduction in Californian emission is 13.4%. Electricity production in California is, on average, less CO_2-intensive than imported electricity, so the policy increases production of electricity in California at the expense of electricity imports. In aggregate, leakage to electricity exporters is -35%, which is driven by leakage to Arizona (-17%) and Utah (-9%).

Although there is negative leakage to electricity exporters, this is partially offset by positive leakage (29%) to other US regions due to changes in both trade and fossil fuel prices (see Table Table 7). 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 US regions. The major sources of leakage to other US regions via the trade channel are increased Californian imports of Chemical, rubber and plastic products from Texas and the South Central region. Overall, positive leakage to other US and international regions is mostly offset by negative leakage to electricity exporters and the aggregate leakage rate is 1.5%. Our results indicate that although tariffs on imported electricity and a ban on resource shuffling significantly increase the price of

CO_2 allowances, these measures can essentially eliminate 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, so the common permit price is close to the EU autarky price, but the Californian electricity tariff still has an impact on the common permit price. As permit 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^{noTariff} scenario, there are only small changes in the permit price in California and the EU relative to the corresponding case without permit trading. Leakage to US 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.

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 in California (the denominator for leakage calculations), so there is only a small change in leakage to electricity exporters in the CA-TRD^{noShuffling} scenario relative to the CA^{noShuffling} case. Permit trading also increase leakage to international regions significantly (from 7% to 46%), which is driven by the increase in the permit price in the EU and associated fossil fuel price and trade effects. 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. Overall, trading permits between the EU and California results in a small increase in leakage from the combined systems (from 22% to 23% with no electricity tariffs and from 18% to 19% when there is electricity tariffs an no resource shuffling).

4.5 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 and permit prices for aggregated regions in the $\text{CA}^{\text{noTariff}}$ and $\text{CA}^{\text{noShuffling}}$ 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 5. In the $\text{CA}^{\text{noTariff}}$ scenario, decreasing σ_i^{DU} reduces substitution away Californian 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

Table 8: Leakage rates (%) and CO_2 prices (2004\$/tCO_2) for alternative Armington elasticity values.

	$\sigma_i^{DU} - \sigma_i^{SU}$				
	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 $\sigma_i^{SU} = 8\sigma_i^M$).

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. Increasing import elasticities (High-High) decreases abatements costs and also 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.

In the $CA^{noSuffling}$ 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 both the Low-Low and High-High cases is 10% and 11% respectively, but leakage rates are still much lower than in the $CA^{noSuffling}$ scenario. Overall, the sensitivity analysis indicates that our findings are reasonably robust to alternative elasticity values in our specification for

US imports and that the results are more sensitivity 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 US. 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.

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. When these characteristics are not included, leakage from the policy was 46% of the decrease in emissions in California. This was driven by leakage of 54% to regions exporting electricity to California. There was negative leakage to other US and international regions largely due to a decrease in the relative price of natural gas. Leakage was also 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. When we included electricity tariffs and did not allow resource shuffling, leakage to electricity exporters was -35% and positive leakage to other resulted in total leakage of 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 will be not 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 Californian emission 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 US states than international regions. Finally, we considered leakage when there was trading of emission permits between California and the EU-ETS. We found that international permit trading resulted in a small increase in aggregate leakage from the two systems.

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