Leakage from Sub-national Climate Policy: The Case of California's Cap-and-Trade Program

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ABSTRACT

With federal policies to curb carbon emissions stagnating in the U.S., 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 45% 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 partially offset leakage elsewhere and overall leakage is 9%.

Keywords: Climate policy, Cap-and-trade, California, Electricity imports, Resource shuffling, Computable general equilibrium, State-level climate policy, Border effect

http://dx.doi.org/10.5547/01956574.36.2.8

1. INTRODUCTION

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. Many

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studies including McCallum (1995) and Anderson and van Wincoop (2003) identify a strong "border effect" causing trade between U.S. states to be considerably larger than trade between states and Canadian provinces. Sub-national climate policies should thus suffer from larger domestic leakage rates than what is usually estimated across national borders, as trade flows more freely between states. However, there is evidence that state borders also limit trade (Wolf (2000), Coughlin and Novy (2011)) and that economic activity is very local, a fact that should limit estimates of domestic leakage. We provide a framework which captures both of these effects.

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

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

General equilibrium assessments of leakage from federal policies commonly estimate leakage rates between 10% and 30% (see, for example, Felder and Rutherford, 1993; 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 U.S. economy. The authors estimate that 49–57% of emissions abated by RGGI electricity generators will be offset by unconstrained sources. A shortcoming in the framework employed by Sue Wing and Kolodziej (2008) is that states source intranational imports from a national pool of 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 the calibration of the model to a dataset which includes 15 U.S. states or aggregated regions and 15 countries or regions in the rest of the world. The model tracks bilateral trade among all regions, including trade among U.S. regions and trade between U.S. regions and international regions. Due to its detailed treatment of trade flows, our model is ideally suited to examining leakage from sub-national climate initiatives in an economy-wide setting.

Several studies have investigated leakage from sub-national climate policies in the U.S. employing a partial equilibrium analysis. Fowlie (2009) analyzes leakage from an incomplete, market-based regulation of carbon dioxide (CO_2) emissions in California's electricity sector using

1. Goulder and Stavins (2011) analyze interactions between federal and sub-national climate policies. They raise the concern that in a framework of overlapping state and federal regulation, state-level efforts may fail to reduce greenhouse gas emissions nationally and may reduce the cost effectiveness of the overall national effort.

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a stylized partial equilibrium, asymmetric oligopoly model. She finds that regulation that exempts out-of-state producers achieves approximately one-third of the total emissions reductions achieved under complete regulation at more than twice the cost per ton.

Bushnell and Chen (2012) use a model of the electricity sector for the western U.S. to examine the impact of alternative cap-and-trade designs. They find that an emissions cap only in California results in substantial leakage to other states. Chen, Liu and Hobbs (2011) simulate a market equilibrium model for electricity markets, transmission limitations and emissions trading. They find that total emissions reductions due to California's cap-and-trade policy are essentially zero when there is resource shuffling and that preventing resource shuffling results in a significant increase in the carbon price. Chen (2009) uses transmission-constrained electricity market models with an exogenous CO_2 permit price to investigate CO_2 leakage (and NO_x and SO_2 emission spill-overs) from the RGGI cap-and-trade program. His key result is that a larger CO_2 price is associated with higher allowance prices, but that leakage rates are falling with the CO_2 price.[2]

This paper has five 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 has finalized details of a cap-and-trade program on 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 CO_2. The first phase of compliance for the program began on January 1, 2013. Covered entities in the first phase include electric utilities, electricity importers, and industrial facilities that emit 25,000 metric tons or more of carbon dioxide equivalent (CO_2e) annually. Industrial sources covered by the policy include petroleum refiners, producers of cement, iron, steel, glass and lime, and pulp and paper manufacturing.

Requiring allowances to be turned in for the emissions embodied in imported electricity is similar to imposing an electricity tariff. According to the legislation, emissions embodied in imported electricity are calculated as the sum of emissions from "specified" and "unspecified" sources, with adjustments for electricity from eligible renewable sources, electricity that is imported and exported during the same hour, and electricity from regions with a cap-and-trade policy linked to California's. 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

2. Not directly focused on leakage but related to sub-national climate policy, Ruth et al. (2008) use the Haiku model, a national electricity market model, and a regional model that includes market power and an input-output model to investigate the energy and economic implications for the state of Maryland joining the RGGI system. Also using the Haiku model, Burtraw, Kahn and Palmer (2006) focus on the implications of the RGGI program for the value of electricity-generating assets for regions in- and outside of the RGGI system.

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reduce its CO_2 liability by sourcing low-emissions electricity from a new source and diverting high-emissions sources previously sent to California to other states. However, such actions may be prevented by regulations that prohibit "resource shuffling", which is defined as "any plan, scheme, or artifice to receive credit based on emissions reductions that have not occurred, involving the delivery of electricity to the California grid" (CARB, 2011, p. 38). As enforcing the bill's resource shuffling regulations may require California to sanction importers based on actions by out of state third parties, the resource shuffling legislation raises several legal issues (Linklaters, 2011).

The second phase of compliance will commence on January 1, 2015 and will expand the set of covered entities to include an estimated 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). At the program's inaugural auction in November 2012, emission permits traded for $10 per metric ton of CO_2 (tCO_2) and were trading at $14/$tCO_2$ in the middle of 2013.

CARB (2011, Subarticle 12, p. A-153) also sets out conditions for linking the Californian program to other trading schemes. Once an external ETS has been approved by the CARB, compliance instruments issued by other programs may be used to meet 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 with five member states with a goal of reducing region-wide emissions by 15% from 2005 levels by 2020 and grew to include seven U.S. states and four Canadian provinces in July 2008. 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, only California and Quebec had 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 and in November 2011 all U.S. states except California left the initiative. However, in May 2013, California and Quebec signed an agreement to link both regions' cap-and-trade systems from the beginning of 2014.

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 regimes 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 such as California's (European Union, 2009, p. 81).

3. MODELING FRAMEWORK

3.1 Data

This study makes use of a comprehensive energy-economy dataset that features a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade for the year 2004. The dataset merges detailed state-level data for the U.S. with national economic and energy data for regions in the rest of the world and is described in detail by Caron and Rausch (2013). Social accounting matrices (SAMs) in our hybrid dataset are based on data from the Global Trade Analysis Project (GTAP, 2012), IMPLAN (IMpact

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Table 1: Data Sources

Data and parameters	Source
Social accounting matrices, bilateral trade	
international regions	Global Trade Analysis Project (GTAP, 2012), Version 7
U.S. states	IMPLAN (2008) and gravity model (Lindall et al., 2006)
U.S. state-to-country bilateral trade flows	Origin of Movement (OM) and State of Destination (SD), U.S. Census Bureau (2010)
Physical energy flows and energy prices	
international regions	GTAP (2012)
U.S. states	State Energy Data System (SEDS), EIA (2009)
Trade elasticities	GTAP (2012) and own calibration
Energy demand and supply elasticities	Paltsev et al. (2005)

analysis for PLANning) data (IMPLAN, 2008), and U.S. 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 U.S. states (and the District of Columbia). The dataset includes input-output tables for each state and identifies 509 commodities as well as tax rates. 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).[3]

Data describing trade between regions outside of the U.S. are taken from the GTAP database 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).[4] As our results depend on benchmark electricity trade flows between California and neighboring states, we replace state-to-state electricity flows from IMPLAN with data from the National Renewable Energy Laboratory's ReEDS model (Short et al., 2009). The ReEDS model simulates electricity flows between 136 Power Control Areas (PCAs) and represents existing transmission constraints. Bilateral U.S. state-to-country trade flows are based on the U.S. Census Bureau Foreign Trade Statistics State Data Series (U.S. Census Bureau, 2010). Exports are taken from the Origin of Movement (OM) data series and imports from the State of Destination (SD) data series.[5] The OM and SD data sets are available at the detailed 6-digit HS classification level, which permits aggregation to GTAP commodity categories.

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

4. 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.

5. 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.

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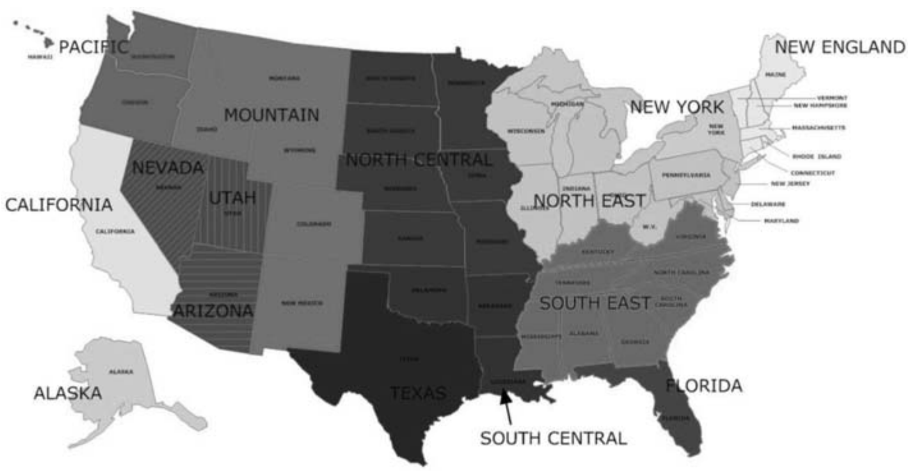
Table 2: Regional and Sectoral Aggregation in the Model

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

Note: * denotes sectors covered in the California ETS.

Figure 1: U.S. Regional Aggregation



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

For this study, we aggregate the dataset to 15 U.S. regions, 15 regions in the rest of the world, and 14 commodity groups (see Table 2). Countries identified in the model include Brazil, Canada, China, India, Japan, Mexico and Russia. EU member states are included in a composite region and several other composites are included for other world regions. The composition of U.S. regions is illustrated in Figure 1. A separate region is included for some states, including California and states that trade electricity with California, but most U.S. regions include several states. Our commodity aggregation identifies five energy sectors and nine non-energy composites. Primary

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factors in the dataset include labor, capital, and fossil-fuel resources. Labor and capital earnings represent gross earnings denominated in 2004 U.S. dollars. The calculation of gross returns to each fossil-fuel resource is outlined in Section 3.2.5.

3.2 The Numerical Model

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

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}):[6]

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

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:

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

where α and v 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 the 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: $Y_{ir}^v = \min(L_{ir}^v, K_{ir}^v, R_{ir}^v, X_{qir}^v, \ldots, X_{Iir}^v)$.

In each region, a single government entity approximates government activities at all levels:

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

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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):

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

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-U.S. and international trade

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

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

$$X_{ir} = [\psi^z ZD_{ir}^{\rho_i^D} + \xi^z ZM_{ir}^{\rho_i^D}]^{1/\rho_i^D} \quad (4)$$

$$C_{ir} = [\psi^c CD_{ir}^{\rho_i^D} + \xi^c CM_{ir}^{\rho_i^D}]^{1/\rho_i^D} \quad (5)$$

$$I_{ir} = [\psi^i ID_{ir}^{\rho_i^D} + \xi^i IM_{ir}^{\rho_i^D}]^{1/\rho_i^D} \quad (6)$$

$$G_{ir} = [\psi^g GD_{ir}^{\rho_i^D} + \xi^g GM_{ir}^{\rho_i^D}]^{1/\rho_i^D} \quad (7)$$

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

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

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

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Figure 2: Aggregation of Local, Domestic, and Foreign Varieties of Good *i* for U.S. Region *s*

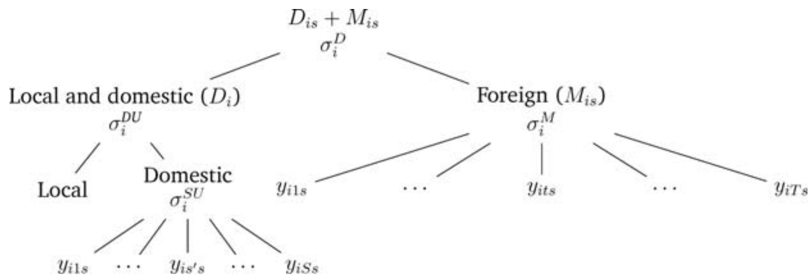
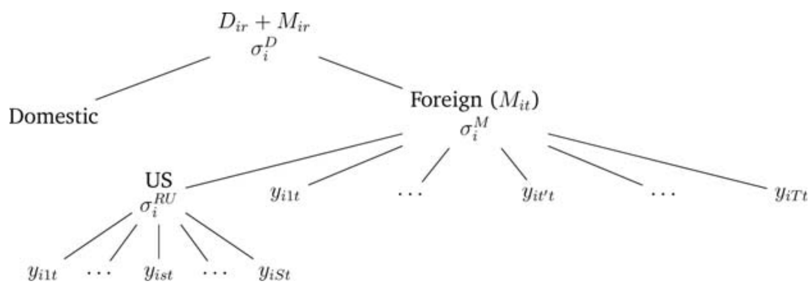


Figure 3: Aggregation of Domestic and Foreign Varieties of Good *i* for International Region *t*



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

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

where η is a CES share coefficient, and $\sigma_i^{DU} = 1/(1-\rho_i^{DU})$ is the implied substitution elasticity between the local variety and a CES composite of intra-U.S. varieties. $\sigma_i^{SU} = 1/(1-\rho_i^{SU})$ is the elasticity of substitution across U.S. origins. Figures 2 and 3 depict the nesting structures described by Eqs. (4)–(9).[7]

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

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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 which maximizes its utility subject to the budget constraint that consumption equals income:

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

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. $\overline{K}$, $\overline{VK}$, $\overline{R}$, $\overline{L}$ and T are benchmark stocks of capital, vintaged capital, fossil fuel resources, labor, and transfer income.

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

Given input prices gross of taxes, firms maximize profits subject to the technology constraints. Minimizing input costs per unit of output yields unit cost indices (marginal costs) p_{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: $GOV_r = TAX_r - T_r - B_r$, where TAX, T_r , and B are tax revenue, transfer payments to households and the initial balance of payments. Aggregate demand by the government is given by: $GD_r = GOV_r / p_r^G$ where p_r^G is the price of aggregate government consumption.

Market clearance equations for factors that are supplied inelastically are straightforward. The other market clearing equations are: (1) Supply to the domestic market equals demand by industry, households, investment, and the government, (2) import supply of good *i* satisfies domestic demand by industry, households, investment, and the government for the imported variety, (3) trade between all regions in each commodity is balanced, and (4) labor supply equals labor demand.[8]

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 benchmark calibration

We use prices and quantities from the integrated economic-energy dataset described in section 3.1 to calibrate the value share and level parameters in the model. Response parameters in the functional forms which describe production technologies and consumer preferences are deter-

8. An online appendix to this paper provides a complete algebraic description of the equilibrium conditions of the model.

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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^{SU}	Across U.S. origins for U.S. regions	$1-\delta+\delta\sigma_i^M$
σ_i^{RU}	Across U.S. origins for international regions	$1-\delta+\delta\sigma_i^M$
σ_i^{DU}	Local—domestic for U.S. regions	$\sigma_i^{SU}/2$

Note: Unless otherwise stated, parameter values for the base case are taken from Paltsev et al. (2005). Substitution elasticities for fossil fuel, and nuclear resource factors are calibrated according to Eq. (11) using the following estimates for price elasticities of supply: $\zeta_{COL} = \zeta_{GAS} = 1$, $\zeta_{CRU} = 0.5$, and $\zeta_{NUC} = 0.25$. σ_l is calibrated assuming that the compensated and uncompensated labor supply elasticity is 0.05 and 0.3, respectively.

mined by exogenous elasticity parameters, the values of which are shown in Table 3. Armington trade elasticity estimates for the domestic to international trade-off are taken from GTAP as estimated in Hertel et al. (2007). The two-level nest between domestic and international goods generates a form of border effect in which international goods are seen to be closer substitutes to each other than to domestic goods. Modeling domestic trade requires additional response parameters in $\sigma_i^{RU}, \sigma_i^{DU}$ and σ_i^{SU}. There are, to our knowledge, no available econometric estimates of these elasticities. Estimating them would require exogenous data on intranational trade costs, the collection of which is beyond the scope of this study.

However, Wolf (2000), Coughlin and Novy (2011) and others have identified the existence of a domestic (or intra-national) border effect.[9] Estimates from Coughlin and Novy (2011) are

9. This is usually done in a gravity framework by including border dummies in a log-linear regression with exporter and importer fixed effects and controlling for distance and other bilateral trade cost proxies.

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relevant to our calibration as they rely on the same trade datasets as we do (the Commodity Flow Survey for domestic trade and the Origin of Movement series for state-to-country trade). Their framework allows them to find the domestic border to effect to be larger than the international border effect by a factor of $\delta = 1.864$.[10]

Our Armington model does not include intra-national trade costs, but does allow for different Armington elasticities of substitution and thus trade elasticities. For each sector, our strategy is thus to back out the elasticity of substitution between goods from different U.S. regions (σ_i^{SU}) using the elasticity of substitution between goods from different international regions (σ_i^M) taken from Hertel et al. (2007) and defining the relationship between the two elasticities using the ratio of the intranational border effect to that of the international border effect (δ). That is, we solve for (σ_i^{SU}) such that $\delta = \frac{(1-\sigma_i^{SU})}{(1-\sigma_i^M)} = 1.864$.

This allows the import demand elasticities for domestic goods (from other states) to be higher than those for international goods. Although δ is identical across sectors, cross-sectoral variability in σ_i^{SU} is identified from the estimates of σ_i^M. Similar to $\sigma_i^D, \sigma_i^{DU}$ is set to be half the value of σ_i^{SU}. We also assume that the elasticity of substitution between goods from different U.S. regions consumed in the in U.S. equals that for U.S. goods consumed in international regions $\sigma_i^{SU} = \sigma_i^{RU}$. 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 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 $\zeta_{\mathrm{COL}} = \zeta_{\mathrm{GAS}} = 1$ and $\zeta_{\mathrm{CRU}} = 0.5$. In a similar fashion, we calibrate the substitution elasticity between the value-added composite and the sector-specific resource factor for nuclear electricity generation ($\zeta_{\mathrm{NUC}} = 0.25$). We set $\zeta_{\mathrm{NUC}} = 0$ for all U.S. regions reflecting our assumption that nuclear generation cannot expand beyond current levels, which we believe is consistent with current political realities and with the 10-year horizon of our analysis. The supply response of renewable electricity is calibrated by setting ζ_{RNW} equal to the generation-weighted average of own-price supply elasticities for hydro and renewable electricity, where weights for generation by source are derived from EIA (2009). Following Paltsev et al. (2005), we set the own-price elasticities of supply from hydroelectricity to 0.5.

Specification of the advanced "backstop" technology that we use to represent electricity from (a generic category of) renewable sources must rely on data beyond that contained in National

10. Specifically, after redefining local trade (not international trade) as the reference, Coughlin and Novy (2011) estimate that the coefficients on the international border dummy, $\beta = (1-\sigma)\tilde{\beta}$, is -1.1 and that on the intranational border dummy $\gamma = (1-\sigma)\tilde{\gamma}$ is -2.05. Given the lack of observable trade costs, the effect of the elasticity of substitution, σ, cannot be distinguished from the true border effects, $\tilde{\beta}$ and $\tilde{\gamma}$. However, the relative strength of the two border effects (δ), can be determined by noting that $\delta = \frac{(1-\sigma)\tilde{\beta}}{(1-\sigma)\tilde{\gamma}} = \frac{\tilde{\beta}}{\tilde{\gamma}} = 1.864$.

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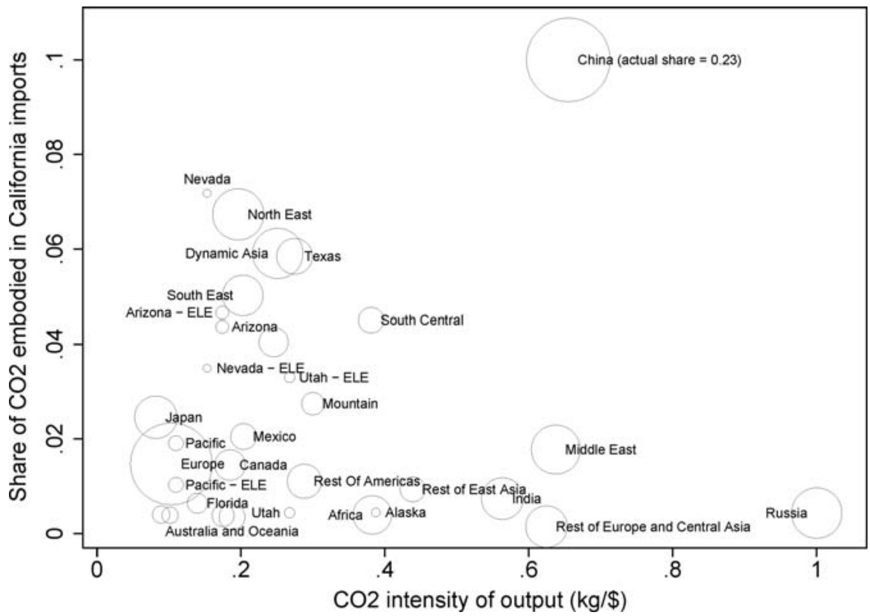
Figure 4: Share of Embodied Carbon in California's Imports against Carbon Intensity of Trading Partner



Note: Size of bubbles denotes benchmark CO_2 emissions. "ELE" denotes electricity trade.

Income and Product Accounts (NIPA) because the production levels and inputs are not identified in the input-output tables underlying our model. By convention, we set input shares so that they sum to unity, and we then separately identify a multiplicative markup factor that describes the cost of the advanced technology relative to pulverized coal. We assume that the backstop technology is relatively capital-intensive and calibrate the dual cost function using a value share of 0.7 for capital.[11] Using the same approach as characterized by Eq. (11), we incorporate for each region a supply curve for renewables. As our base case, and in line with econometric evidence from Johnson (2010), we employ an own-price elasticity of supply of renewable electricity generation of 2.7.

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

3.3 Descriptive Analysis of the Data

Figure 4 displays, for each of California's trading partners, the CO_2 intensity of output, the share of CO_2 embodied in California's imports attributable to that region,[12] and total regional

11. We have performed sensitivity analysis with regard to input shares of the backstop technology and find that our assumptions do not materially affect our conclusions.

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

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CO_2 emissions (represented by bubble size). In aggregate, U.S. regions account for 23% of global CO_2 emissions. The next largest emitters are China (17%) and the EU (14%). The largest sources of U.S. emissions are the North East (27% of U.S. emissions and 6% of global emissions), the South East (17% and 4%) and Texas (13% and 3%). Californian emissions (not shown in Figure 4) are 5.5% of total U.S. emissions (and 2% of global emissions). As Californian emissions are a small proportion of global emissions, large leakage rates from California 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 (23%), followed by Nevada, the North East, Dynamic Asia and Texas. Electricity accounts for one-quarter of California's total imported emissions, mostly from Arizona (35%), Nevada (27%) and Utah (25%). 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 U.S. regions are displayed in Figure 5. Compared to electricity generated in California, electricity from Utah is six times as carbon-intensive, electricity from Arizona and Nevada twice as carbon intensive, and electricity from the Pacific region is less carbon-intensive. In other regions, electricity in the Mountain, North Central and North East regions are relatively carbon-intensive. High carbon intensities in these (and other) regions are due to large shares of coal-fired generation. In contrast, emissions from natural gas account for 92% of total electricity emissions in California.

4. MODELING RESULTS

4.1 Scenarios

We evaluate leakage from California's cap-and-trade program in 2020. So that our benchmark dataset more accurately reflects this year, we implement a forward calibration exercise prior to implementing our policy scenarios. For our analysis, an important future development is the share of electricity generation from renewable sources. Reflecting policy incentives for renewable electricity and decreasing costs for these technologies and guided by targets set out in Short et al. (2009) (for U.S. regions) and (MITJPSPGC, 2012) (for international regions), we increase renewable electricity shares by changing the endowment of the fixed factor input required for renewable electricity production.

We consider six policy scenarios. The first, "EU-ETS," simulates a cap-and-trade program in the EU. This scenario serves as a point of comparison and allows the identification of the leakage risks of sub-national policies such as California's relative to national policies. The EU-ETS aims to reduce 2020 emissions by 21% relative to 2005 emissions. The actual reduction in EU emissions in 2020 due to the ETS will be influenced by, among other factors, regulations regarding the use of offsets, the banking of allowances for use in phase three of the EU-ETS, development of the EU's renewable portfolio standard, and whether or not the EU proceeds with plans to implement a more ambitious 2020 cap. We evaluate the impact of the EU-ETS, net of complementary measures, by imposing a cap that reduces EU emissions in covered sectors by 20%. Reflecting current leg-

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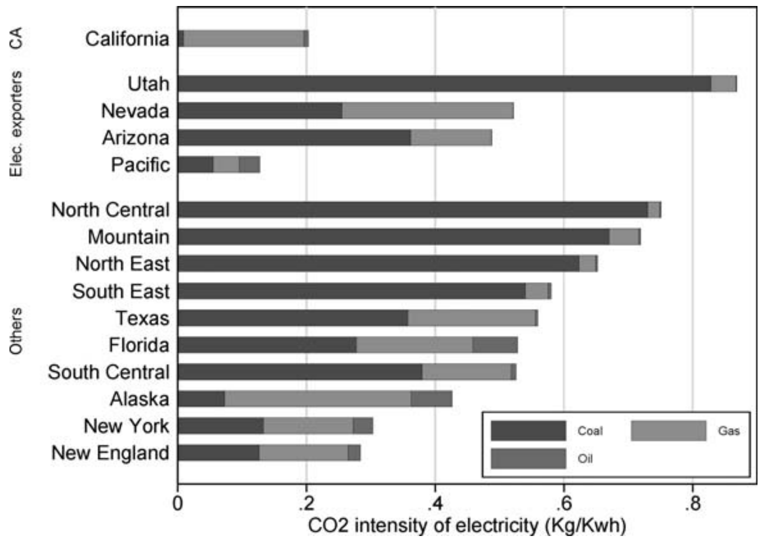
Figure 5: Kilograms of CO_2 Emissions per kWh of Electricity Produced



islation, we apply the cap to emissions from Electricity; Oil refining; Chemical, rubber and plastic products; Ferrous metals; Metals nec; Mineral products; and Paper products and publishing.

The other five scenarios all include a cap on Californian emissions. However, the EU emissions cap is still imposed in these scenarios and all impacts will be expressed relative to values in the EU-ETS scenario. The reduction in Californian emissions due to the cap-and-trade program will depend on emissions reductions due to complementary measures, such as California's Low Carbon Fuel Standard and Renewable Portfolio Standard, Senate Bill 1368 (which prevents long-term investments in state-owned generation facilities that do not meet an emissions performance 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.[13] 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 reduction in leakage in states producing (on average) relatively carbon-intensive

13. 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 by 18% relative to business as usual (i.e., a case with no climate policies), and 20% of this decrease is due to the cap-and-trade policy when offsets are used and 37% when there are no offsets.

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electricity. We implement three scenarios to tease out the impact of different aspects of California's policy. In the $CA^{noTariff}$ scenario, we consider a cap on Californian emissions without electricity tariffs or legislation to prevent resource shuffling. This scenario will allow the identification of the importance of electricity tariffs. In the $CA^{Shuffling}$ 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 $CA^{Shuffling}$ 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 $CA^{noShuffling}$ scenario, we calculate emissions embodied in imported electricity using emission coefficients in exporting regions from the 2020 baseline data and set the elasticity of substitution between California's electricity imports from different regions (σ_i^{SU}) equal to zero. This scenario thus implicitly assumes that the ban on resource shuffling prevents importers from adjusting the composition of electricity to reduce CO_2 liabilities. Our $CA^{noShuffling}$ scenario includes all aspects of California's cap-and-trade policy and is therefore the most accurate representation of this legislation. In all 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, $CA\text{-}TRD^{noTariff}$, allows trading of permits between the two systems without a tariff on Californian imports of electricity. The other, $CA\text{-}TRD^{noShuffling}$, considers trading of permits with Californian electricity tariffs and no resource shuffling.[14]

Finally, in the EU-ETS, $CA^{noTariff}$ and $CA^{noShuffling}$ scenarios, we implement a counterfactual exercise to distinguish the leakage occurring via the trade channel from that occurring through the fossil fuel price channel. Leakage due to trade is estimated by holding the price of fossil fuels constant in all regions and fossil fuel-price leakage is calculated as total leakage (simulated in our core scenarios) minus leakage due to trade. As relative commodity prices change when fossil fuel prices are constant, leakage attributed to trade in our analysis includes leakage due to changes in demand.[15]

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 U.S. regions, (ii) to international regions, (iii) due to changes in electricity production, and (iv) total leakage. Leakage to each region is calculated as the increase in emissions in that region divided by the decrease in European emissions in the EU-ETS scenario, and the decrease in emissions in California in scenarios that consider California's cap-and-trade program (all other scenarios). In the scenarios that consider electricity tariffs, the reduction in Californian emissions depends

14. We do not evaluate the impact of linking cap-and-trade programs in California and Quebec, as our modeling framework does not have sub-regional detail for Canada.

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

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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		11.9	21.0	61.2	14.7	18.5
EUR	15.0	15.0	15.0	15.0	14.7	18.5
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	−7.8	−13.6	−6.1	−4.9
% of CA benchmark—global		−3.3	−4.7	−12.7	−2.8	−13.9
Leakage rate (%)						
from individual policy						
Total	20.0	45.1	45.5	8.5	51.1	47.1
Electricity	15.2	43.7	37.5	−13.3	42.8	22.7
to U.S.	1.5	49.1	44.8	1.3	50.6	1.0
International	18.5	−4.2	−0.7	7.1	−5.5	46.0
from CA and EU policies combined						
Total	20.0	21.5	22.5	18.0	22.2	18.9

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

	EU-ETS	$CA^{noTariff}$	$CA^{Shuffling}$	$CA^{noShuffling}$	$CA\text{-}TRD^{noTariff}$	$CA\text{-}TRD^{noShuffling}$
Total U.S.	1.5	49.1	44.8	1.3	50.6	1.0
Total Elec. Exporters	0.0	48.5	34.2	−26.9	48.9	−26.1
Nevada	0.0	6.8	−0.6	−2.4	6.7	−2.1
Pacific	0.0	6.4	12.6	−3.9	6.5	−4.1
Utah	0.0	13.7	−1.5	−7.5	14.0	−7.3
Arizona	0.0	21.7	23.7	−13.1	21.7	−12.7
Total Rest of U.S.	1.6	0.6	10.6	28.3	1.8	27.2
North East	0.2	−4.4	−3.0	2.4	−3.9	0.6
North Central	0.2	−4.3	−4.0	−1.6	−4.1	−1.9
South East	0.4	−2.4	1.1	4.4	−2.0	3.4
South Central	0.0	−0.6	0.0	0.7	−0.4	0.1
New England	0.0	0.7	0.9	1.1	0.5	1.6
Alaska	0.0	0.6	0.6	0.8	0.6	0.9
New York	0.0	1.4	1.0	0.7	1.2	1.5
Florida	0.0	1.5	1.3	1.1	1.4	1.6
Mountain	0.4	0.8	3.6	7.1	0.7	9.7
Texas	0.2	7.2	9.2	11.6	7.8	9.8
International regions	18.5	−4.1	0.7	7.1	−5.5	46.0
All regions	20.0	45.1	45.5	8.5	45.1	47.1

on the quantity of permits used for imported electricity. Consequently, the denominator for leakage calculations varies across scenarios.

Table 5 disaggregates leakage rates by region for each scenario and Table 6 disaggregates leakage among sectors for the core $CA^{noShuffling}$ scenario. To assess the contribution of changes in trade and fossil fuel prices, leakage due to each channel for aggregate regions for selected scenarios is reported in Table 7. By design the last panel of Table 7 replicates aggregate results reported in Table 5.

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Table 6: Leakage by Sector in the CA^{noShuffling} Scenario

	Elec. Exporters	Rest of U.S.	U.S. Total	International	Total
Electricity	−28.8	13.0	−15.8	2.5	−13.3
Natural gas	−0.3	−4.4	−4.8	0.0	−4.8
Coal	0.0	0.0	0.1	0.0	0.1
Petroleum and coal products (refined)	0.0	2.6	2.6	0.0	2.6
Ferrous Metals	0.0	0.0	0.0	0.0	0.0
Non-ferrous metals	0.0	0.0	−0.1	0.0	0.0
Other manufacturing	0.0	0.0	−0.1	0.1	0.1
Paper and Products and publishing	0.0	0.0	0.0	0.0	0.1
Non-metallic minerals	0.0	0.2	0.2	0.0	0.2
Other energy intensive sectors	0.1	0.3	0.4	0.1	0.5
Agriculture	0.0	0.4	0.5	0.2	0.7
Services	0.1	0.9	1.0	0.2	1.2
Chemical, Rubber and Plastic products	0.0	2.8	2.8	0.4	3.1
Transportation	1.0	8.0	9.0	3.2	12.2
Final demand	1.1	4.6	5.7	0.3	6.1

In the EU-ETS scenario, the allowance price is \$15/tCO_2 and the leakage rate to all regions is 20% of the reduction in EU emissions. Leakage rates to all regions are positive and the largest sources of leakage are Africa and China. U.S. emissions increase by 1.5% 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 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.[16] The allowance price reduces Californian electricity production by 9% and there is a decrease in the demand for natural gas. Without an electricity tariff, importing electricity is a low-cost channel for California to reduce emissions from domestic sources, which results in high leakage to electricity exporters. The largest leakage sources are Arizona (22%), which experiences the largest increase in electricity exports to California, and Utah (14%), the most carbon-intensive electricity exporter. Decreasing electricity production in California and increasing production in neighboring states decreases the price of natural gas and increases the price of coal. These price changes drive changes in emissions in other U.S. regions. In regions with a high proportion of electricity generated from coal, these price changes reduce emissions from electricity. The largest negative leakage rates are observed for the North Central and North East regions; however proportional changes in emissions in 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 (7%) is driven by increased exports of Chemical, rubber and plastic products to California.

16. Using a model of the power sector, Bushnell and Chen (2012) estimate a carbon price of \$11/tCO_2 when California reduces electricity emissions by 15% with no restriction on electricity imports. The higher carbon price in our analysis (for a smaller proportional reduction in emissions) reflects the fact that emissions abatement costs are lower in electricity than

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Table 7: Leakage Due to Fossil Fuel Price and Trade Channels (in %)

	EU-ETS	$CA^{noTariff}$	$CA^{noShuffling}$
Trade:			
Elec. Exporters	0.0	57.4	−28.0
Rest of U.S.	1.5	−1.9	12.9
International	10.7	4.8	5.9
All regions	12.2	50.3	−9.1
Fossil fuel prices:			
Elec. Exporters	0.0	1.1	1.0
Rest of U.S.	0.1	2.5	15.4
International	7.8	−8.8	1.2
All regions	7.9	−5.2	17.6
All channels:			
Elec. Exporters	0.0	48.5	−26.9
Rest of U.S.	1.6	0.6	28.3
International	18.5	−4.1	7.1
All regions	20.0	45.1	8.5

In the U.S., leakage to electricity exporters is 49% and leakage to other regions is 1%. Leakage to international regions is -4%, as positive leakage via the trade channel is more than offset by negative leakage due to changes in fossil fuel prices.

Finally, aggregate leakage in the $CA^{noTariff}$ scenario is 45%, more than double the leakage rate simulated for the EU-ETS. The large leakage rate is driven by increases in electricity production for export to California. Although there is negative leakage to regions that do not export electricity to California, our results indicate that without electricity tariffs California's cap-and-trade program will not be very effective at reducing emissions.

4.3 The Impact of Electricity Tariffs

Tariffs with resource shuffling. When there are tariffs on imported electricity but no resource shuffling provisions, as in $CA^{Shuffling}$, the Pacific region has sufficient renewable and nuclear capacity to only export carbon-free electricity. Arizona can reduce the CO_2 intensity of electricity exported to California by 83%, whereas Nevada and Utah, which are the most CO_2-intensive suppliers of electricity to California, can only reduce theirs by 50%. As a result, relative to the $CA^{noTariff}$ scenario, Nevada and Utah export less electricity to California (and leakage to these regions decreases) whereas Arizona and the Pacific region export more (and leakage increases). Total leakage to electricity exporters decreases to 34% (from 49% in the $CA^{noTariff}$ scenario). However, leakage to other U.S. regions increases (from 1% to 11%) due to reduced demand for coal in Nevada and Utah and the higher permit price in California. Leakage to international regions increases for the same reason. Aggregate leakage increases slightly from 45% in the $CA^{noTariff}$ scenario to 46% in the $CA^{Shuffling}$ scenario, which indicates that electricity tariffs will not be an effective measure to reduce leakage if resource shuffling takes place.

other sectors. Such cost differences are widely observed in economy-wide analyses of climate policies, see, for example, Winchester et al. (2013).

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Tariffs and no resource shuffling. We now consider a scenario that includes both the electricity tariff and a ban on resource shuffling, $CA^{noShuffling}$, as specified by California's cap-and-trade legislation. In this scenario, the allowance price is considerably higher at \$61/tCO_2 and, due to the use of permits for imported electricity, the actual emissions reduction to take place within California is 13% (instead of 5%). Electricity production in California is on average less CO_2-intensive than imported electricity, so the policy increases the production of electricity within California at the expense of electricity imports. In aggregate, leakage to electricity exporters is −27%, which is driven by emissions reductions in Arizona (leakage of −13%) and Utah (−8%).

However, the negative leakage to electricity exporters is offset by positive leakage (28%) to other U.S. regions due to changes in both trade and fossil fuel prices (see 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 U.S. regions. The major sources of leakage to other U.S. 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 U.S. and international regions is mostly offset by negative leakage to electricity exporters and the aggregate leakage rate is 9%. To conclude, our results indicate that although the inclusion of imported electricity in the cap and a ban on resource shuffling significantly increase the price of CO_2 allowances and that leakage is in a large part simply further displaced (to the rest of the U.S. and internationally), the emissions reductions in electricity exporting states are sufficient to significantly reduce total leakage.[17]

4.4 Trading of Permits between California and the EU

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

In the $CA\text{-}TRD^{noTariff}$ scenario, abatement possibilities are cheaper in California than in Europe, and California reduces its emissions by 6% instead of 5%. Relative to the corresponding case without trading, permit prices increase to \$15 (from \$12). Leakage to U.S. regions increases (from 49% to 51%), mainly due to an increase in California electricity imports. Leakage to international regions falls due to the decrease in the permit price in the EU. The overall leakage rate from the combined policies increases from 21.5% to 22.2%.

When there is an electricity tariff and no resource shuffling, permit trading decreases the price of emissions rights in California (from \$61) and increases it in the EU (from \$15) to \$19. The decrease in the permit price in California decreases the tariff on imported electricity and ultimately increases emissions in regions exporting electricity to California. However, there is also a decrease in emissions abatement within California (the denominator for leakage calculations), so

17. In an additional scenario, we simulated California's cap-and-trade program with border carbon adjustments on imports of all commodities (and no resource shuffling). Relative to the $CA^{noShuffling}$ scenario, these tariffs have little impact on leakage to electricity exporters but reduces leakage to the rest of the U.S. (from 28.3% to 11.2%) and international regions (from 7.1% to 5.8%).

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Table 8: Leakage Rates (%) and CO_2 Prices (2004$/t$CO_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 ($/t$CO_2$)—CA	11.9	14.4	12.1	14.7	8.6
Leakage rate (%)					
Total	45.1	29.7	41.2	27.0	68.8
Electricity	43.7	27.9	41.2	27.0	68.8
to U.S.	49.1	32.1	44.7	28.7	76.0
International	−4.1	−2.4	−3.5	−1.8	−7.2
CA^{noShuffling}					
Carbon Price ($/t$CO_2$)—CA	61.2	64.5	62.0	65.6	55.1
Leakage rate (%)					
Total	8.5	12.4	8.6	12.0	1.4
Electricity	−13.3	−4.3	−12.2	−3.3	−32.6
to U.S.	1.3	5.0	0.7	3.9	−4.0
International	7.1	7.4	7.8	8.1	5.4

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" elasticities values are twice as large as base values ($\sigma_i^{DU} = 4\sigma_i^M$ and $\sigma_i^{SU} = 8\sigma_i^M$).

there is only a small change in leakage to electricity exporters in the CA-TRD^{noShuffling} scenario relative to the CA^{noShuffling} case. The decrease in the price of coal increases electricity emissions in other regions so leakage due to changes in electricity production is 23%, even though there is negative leakage to regions exporting electricity to California. Allowing permit trade between the EU and California again results in a small increase in leakage from the combined systems (from 18% to 19%). Thus, we have found that from the EU's perspective, permit trade with a sub-national region such as California—whose economy is tightly integrated with other states'—leads to a modest increase in overall leakage rates, whether or not electricity tariffs are implemented.

4.5 Sensitivity Analysis

A key driver of our results is that changes in California have larger impacts on U.S. regions than international regions. Accordingly, we consider "Low" and "High" alternative values for elasticities governing substitutability in U.S. demand between domestic and imported production (σ_i^{DU}), and among imports from U.S. regions (σ_i^{SU}). Our low and high alternative values for σ_i^{DU} and σ_i^{SU} are, respectively, half and twice the base values of these elasticities.

Leakage rates and permit prices for aggregated regions in the CA^{noTariff} and CA^{noShuffling} scenarios are presented in Table 8. The first component of case labels convey values for σ_i^{DU} and the second component values for σ_i^{SU}. In the CA^{noTariff} scenario, decreasing σ_i^{DU} reduces substitution away from 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 decrease in aggregate leakage in the Low-Base case relative to our core case. Decreasing the value of σ_i^{SU} (Base-Low) has only a minor impact on leakage and the permit price as changes in relative prices of imports from different sources are small. Increasing import elasticities (High-High) decreases abatements costs and the permit price, and increases substitution towards imported electricity. As a result, there

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is a larger increase in leakage to electricity exporters, which is partially offset by a decrease in leakage to other regions. Overall, we find that despite uncertainty in the estimates of total leakage (it ranges from 27% to 69%), it remains in all cases higher than leakage estimates generally found for national policies.

In the $CA^{noShuffling}$ scenario, as σ_i^{SU} is set to 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 (8.6%) is similar to that in the Base case (8.5%). Leakage in the Low-Low and High-High cases is 12% and 1% respectively, and in all cases leakage rates remain much lower than in the $CA^{noShuffling}$ scenario. Overall, the sensitivity analysis indicates that our findings are reasonably robust to alternative elasticity values and that the results are more sensitive to scenario assumptions than alternative Armington elasticity values. Moreover, our conclusion that leakage will be large if there is resource shuffling holds for a range of alternative parameter values.

Despite this robustness, several limitations to our analysis should be noted. First, our modeling framework did not explicitly consider restraints on changes in electricity trade due to transmission or grid integration constraints. Second, as noted above, we did not model complementary climate policies and instead simulated an emissions cap net of complementary measures. If interactions between these measures and California's cap-and-trade program are significant, this simplification may bias our estimates. Third, we did not consider the impact of permit revenue recycling on economic and emissions outcomes. In this connection, Paul et al. (2010) find that allocating permit revenue from the RGGI to energy-efficiency programs reduces electricity consumption.

5. CONCLUSIONS

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

Key features of California's cap-and-trade policy include the requirement that allowances must be surrendered for emissions embodied in imported electricity, which is similar to an import tariff, and provisions to prevent resource shuffling. If these features were not included in the policy, leakage was found to be 45% of the decrease in emissions in California. California's potential for reducing emissions alone would thus be limited. This estimate was driven by leakage of 49% to regions exporting electricity to California. There was negative leakage, in aggregate, to other regions largely due to a decrease in the relative price of natural gas. Leakage remained significant when electricity tariffs were included but out-of-state generators could lower the incidence of the tariff by rerouting electricity transmission so that less carbon-intensive electricity is supplied to California. If such resource shuffling is banned, however, leakage to electricity exporters was -27%. Increases in leakage to other U.S. and international regions compensate for this decrease and total leakage was 9%. These findings indicate that California's cap-and-trade program results in only a small amount of emissions leakage. This conclusion hinges on the enforcement of provisions to prevent resource shuffling: without them, electricity tariffs may not be able to prevent substitution towards imported electricity. A corollary of this conclusion is that electricity tariffs are an effective way of expanding the scope of the program, although permits used for imported electricity increased the reduction in 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 U.S. states than international regions. Finally, we

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considered the possibility of allowing trading of emission permits between California and the EU-ETS, and found it to result in a small increase in aggregate leakage from the two systems.

ACKNOWLEDGMENTS

The authors are indebted to John Reilly, Roberton C. Williams III, participants at the 2012 Allied Social Sciences Association Annual Meeting and the 2012 AERE Summer Conference, and two anonymous referees for helpful comments and suggestions.

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