Supplementary Information

Social Cost of Carbon Pricing of Power Sector CO$_2$: Accounting for Leakage and Other Social Implications from Subnational Policies

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1. Literature Review

“ Leakage” refers to regulatory-induced economic and environmental shifts from regulated segments to uncovered (or less stringently regulated) sources. Literature and policy discussions typically focus on leakage from emissions reduction policies, but leakage can occur for any regulation that only applies to a subset of sources while other sources are subject to less restrictive requirements.

Few studies in the literature investigate leakage implications of subnational energy and climate policies. Empirical and modeling studies of leakage typically concentrate on national and international climate policies and have focused on quantifying leakage mechanisms, rates, and impacts on trade (e.g., Böhringer, Balisteri, and Rutherford 2012, Babiker 2005). Previous cap-and-trade systems have provisions to prevent intra- and inter-sector leakage (Goulder and Stavins 2011).

The limited literature on leakage and subnational externality-correcting policies have focused on California and the Regional Greenhouse Gas Initiative (RGGI) states (Caron et al 2015, Fowlie 2009, Chen 2009) for existing policies. This work indicates that unilateral subnational policies are expected to lead to leakage, but there is less certainty about the magnitude of emissions changes and economic impacts in part due to limitations in the scope and modeling of these studies. Some studies illustrate short-run shifts in emissions from controlled to uncontrolled regions but only simulate changes in dispatch with fixed generation fleets and do not investigate the implications of capacity or transmission investment over time (e.g., Sauma 2012, Chen 2009). Other papers in the literature consist of stylized models with restrictive assumptions about policies and potential for electricity trade (e.g., Winchester and Rausch 2013), often with static trade models instead of intertemporal optimization frameworks (e.g., Eichner and Pethig 2015). In addition, studies that examine leakage mitigation measures indicate that, while effective in lowering leakage, these provisions may undermine regulations in other ways (Bushnell and Chen 2012).

Our paper makes several literature contributions. The analysis is the first to evaluate emissions implications of unilateral policies for 14 different geographical areas within the U.S., including emissions changes within the regulated region, across other regions (i.e., geographical leakage), and across other sectors of the economy (i.e., sectoral leakage). Investigating unilateral subnational policies is critical not only due to increased policy focus in light of stalled federal measures in the U.S. but also due to greater market integration across U.S. states compared with national borders. The analysis is also the first to use a linked electric sector and computable general equilibrium (CGE) model to evaluate net emissions changes in power markets and the energy system. The dynamic intertemporal model with power sector detail, hourly cross-border flows, and simultaneous optimization of capacity planning and transmission provide a more realistic representation of investment and dispatch. In addition, the analysis examines impacts under a range of different policy stringencies with different levels of regional power sector CO2 pricing, which provides insight into the relationship between leakage and regulatory stringency. Finally, the analysis investigates not only leakage under unilateral subnational policies but also changes in net emissions and a range of other societal impacts (e.g., macroeconomic costs and price impacts). Previous work typically does not address broader social implications of subnational policies, even though these impacts are important to decision-making.
2. Methods

2.1. Model Structure

This analysis uses the U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model, an energy-economic model that connects a detailed representation of electric-sector investment and dispatch with a dynamic computable general equilibrium (CGE) model of the economy (EPRI, 2014). The model can assess regional implications of multisector, multigas policies and can explore how different assumptions about the technological and policy landscapes may influence transformation pathways in the contiguous United States. The model’s spatial disaggregation allows it to account for regional resource endowments, costs, demand, and regulations. The electric sector module contains added detail to simultaneously capture capacity investment and dispatch decisions for all model regions.

The version of US-REGEN used for this study is organized into 14 state-based regions, as shown in Figure S1. The model solution entails successive iterations between the bottom-up electric-sector model and the top-down CGE model until the target variables converge. The iterative structure is required due to the contemporaneous influence of energy sector price and quantity changes on economic activity and aggregate productivity changes of the economy on electricity consumption. These interactions are especially important under greenhouse gas (GHG) emissions policies, which can induce fuel switching depending on the policy stringency and costs of end-use technologies.

Figure S1. Regional structure of the US-REGEN model

US-REGEN maximizes social surplus (consumer plus producer surplus) but does not account for potential environmental damages to society. The CGE model represents residential, commercial, industrial, transportation, and refining sectors and captures energy efficiency (i.e., end-use tradeoffs between fuels

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1 NE-Central-D and NE-Central-R are aggregated for this analysis.
and capital) through substitution elasticities. To achieve GHG reductions, if incentivized, the model has three broad channels for abatement for different regions, sectors, and GHGs:

1. Fuel switching
2. Energy efficiency adoption (i.e., price-driven improvements)
3. Activity reduction

Hourly load and renewable resource variability by region come from historical, synchronized time-series data from the same year to preserve empirical spatial and temporal variation. Simultaneity and chronological ordering are critical for representing a more complete spectrum of joint variability instead of averaging (which artificially smooths variation) or asynchronous time-series data (which do not capture the joint variation that is critical for system operations and resource adequacy). Wind and solar data come from AWS Truepower and (like the load data) are based on 2010 meteorology. The electric-sector model uses a novel methodology to select representative hours that preserve variability while reducing the problem size by two orders of magnitude (Blanford et al 2016). Although the electric-sector includes variability and dispatch for these representative hours, electrification of additional sectors is assumed to add load uniformly across all hourly segments, which likely understates capacity needs if electrified end-uses do not increase load uniformly.

US-REGEN’s detailed intra-annual temporal resolution and regional heterogeneity are critical for accurately representing power system operations and trade, as many other models do not represent endogenous electricity import, export, and transmission build decisions. Dynamic linkages across geographical areas and interactions among electric sector technologies materially impact dispatch and emissions in electricity markets. These bottom-up details in intertemporal optimization models like US-REGEN are necessary for evaluating leakage and other policy-induced power system changes.

The electric sector and CGE model are deterministic. Thus, the results do not reflect hedging against technological or economic uncertainties that could prove more or less favorable than expected.

Note that this analysis focuses on geographical and sectoral leakage related to production-related emissions changes in aggregate sectors—residential, commercial, industrial, transportation, and refining. Effects on individual industries are not explored; in particular, energy-intensive industries like ferrous and non-ferrous metals, cement, and chemicals. Furthermore, although the US-REGEN model captures the potential for electricity generation to move across regions due to changes in economics and policy, the model does not fully capture possible migration of non-electric firms across state boundaries (Kahn and Mansur 2013). Leakage from the migration of firms and production in energy-intensive industries like ferrous and non-ferrous metals, cement, chemicals, and others is an important area for future research, especially for economy-wide CO2; policies that are expected to have larger impacts on these sectors than the electric-sector-only policies investigated in this analysis.

Greater detail in the assumptions and data underlying US-REGEN are provided in the model documentation (EPRI 2017; Blanford et al 2014).
2.2. Scenario Assumptions

The reference scenario (i.e., without SCC pricing in any region) includes most existing and known future state and federal policies and regulations. Updated state renewable portfolio standards are included along with federal policies like Mercury and Air Toxics Standards (MATS) and Clean Water Act § 316(b). State policies include California’s AB 32 and the Regional Greenhouse Gas Initiative (RGGI) for eastern states. The Clean Air Act § 111(b) and 111(d) CO2 performance standards are not included in the analysis. 2015 tax extenders for wind or solar are also excluded. Rooftop solar is modeled as a separate technology “behind the meter” (i.e., all rooftop generation receives the retail price for electricity) as per current regulatory practice in many states. No forced retirements for existing coal units are included in the reference, though retirements for economic reasons are possible. Fuel prices and energy demand are based on the Energy Information Administration’s Annual Energy Outlook. The natural gas price trajectory comes from the 2015 AEO reference case, which starts at $4.88/MMBtu (2013 dollars) in 2020 and escalates to $7.85 by 2040. EPRI technology costs and limitations (e.g., on the rate and extent of transmission and nuclear deployment) are used.

The analysis focuses on three SCC price trajectories to investigate how SCC pricing levels could affect results: lower (SCCL), middle (SCCM), and higher (SCCH). These trajectories are implemented as taxes on production-based CO2 emissions from the electric sector. Given the issues identified in Rose et al (2014, 2017) associated with multi-model approaches to SCC estimation, we use the SCC trajectories from a single integrated assessment model, FUND, instead of U.S. Government Interagency Working Group values (United States Government Interagency Working Group 2016). The three SCC pathways from Anthoff et al (2011) reflect scientific uncertainty about the sensitivity of the climate system to GHG concentrations. A lower (higher) SCC path results from a less (more) sensitive climate system. The “middle” path (SCCM) has a central equilibrium climate sensitivity value of 3°C. The “lower” (SCCL) and “higher” (SCCH) trajectories have equilibrium climate sensitivities of 2°C and 4.5°C, respectively. These three paths are shown in Figure S2 in units of 2007$ per metric ton CO2. The values differ in 2020 and diverge over time.

Figure S2. Power-sector-only SCC price trajectories
Given the possibility of leakage across regional borders, we analyze a simple leakage-mitigation provision to evaluate the effectiveness and broader implications of such mechanisms. Specifically, we run an “import constraint” sensitivity that prohibits electricity imports into the constrained region above the reference import levels (i.e., levels when there is no SCC pricing).

We also run sensitivities on the following:

- **National electric-sector SCC pricing**: In addition to unilateral regional SCC pricing, we investigate national SCC pricing scenarios with our SCC pricing pathways applied to the entire U.S. power sector to explore leakage through fuel markets into other economic sectors, outside of the electric sector.

- **Constrained power sector transformations**: To examine the impact of greater constraints on expanding electricity imports and exports, this sensitivity assumes no new transmission investments above reference levels across the model’s time horizon.

- **Electricity demand price responsiveness**: To examine the impact of demand responses on our results, this sensitivity assumes price inelastic (i.e., unresponsive) electricity demand.

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2 For instance, issues surrounding resource shuffling and cross-border leakage have been critical in the debate surrounding the design of California’s cap-and-trade market. Although there are many proposals for assuaging these effects, the ultimate form embedded in actual regulations will likely be shaped by a host of region-specific factors.
3. Additional Results

3.1. Northwest-Central Results

Figure S3 shows cumulative leakage (top) and cumulative net emissions changes (bottom) through 2025 and 2040 for the three SCC pricing trajectories in the NW-Central region. Negative leakage implies additional CO₂ reductions outside the NW-Central electric sector, where higher fuel (electricity and gas) prices are suppressing demand. Leakage increases with SCC level, but not in all cases. For the NW-Central region under these scenarios, the cumulative leakage rate varies between -30% and 30%. We also see how import constraints may reduce positive leakage to below 10% and possibly enhance negative leakage with low SCC pricing. Although cumulative net CO₂ reductions increase in policy stringency (higher SCCs), net CO₂ reductions can be lower when import constraints are implemented, as shown in the SCCH results.

**Figure S3.** Cumulative leakage (top) and cumulative net CO₂ change (bottom) to 2025 and 2040 under different SCC pricing trajectories for the NW-Central region with and without import constraints
Figure S4 shows how the regional policy not only impacts the regulated region’s electricity prices but also neighboring region electricity prices. Although the most significant price changes occur for the region imposing SCC pricing (NW-Central in this case), price changes also occur in neighboring regions that are direct electricity trading partners. Note that Mountain-N prices decrease in the import constrained case, while prices in the NE-Central region increase, owing to reduced competition for Mountain-N power and NW-Central renewable power exports.

Figure S5 illustrates differences in disaggregated electric sector costs across the SCC pricing scenarios relative to the reference.

**Figure S4.** Price increases from the reference (%) for neighboring regions under SCCH pricing for the NW-Central region
Figure S5. Difference in NW-Central electric sector costs between the policy scenario and baseline (billion $ present value between 2010 and 2050)

Figure S6 compares 2025 generation, energy for load, and emissions intensity of generation for the NW-Central region under the reference and policy scenarios. For low to moderate SCC trajectories, energy for load decreases along with in-region generation. The highest SCC trajectory entails greater imports and considerably lower emissions intensities from coal-to-wind substitution. Import constraints generally increase in-region load serviced by more expensive in-region generation with higher emission intensities.
**Figure S6.** Generation by technology (TWh) and emissions intensity of in-region generation (t-CO₂ per MWh) in the NW-Central region in 2025 under reference and policy scenarios without and with import constraints (“IC”).

Figure S7 shows generation and power sector emissions intensities for adjacent regions. Changes between scenarios are smaller in unconstrained regions relative to the regulated region. However, all three regions increase exports for the most stringent policy scenario (SCCH) with gas and wind on the margin. With NW-Central import constraints, generation in these regions in 2025 is relatively unaffected by the NW-Central SCC policy.
Figure S7. Generation by technology (TWh) and emissions intensity of in-region generation (t-CO2 per MWh) in the three regions bordering NW-Central in 2025 under reference and policy scenarios without and with import constraints (“IC”).

3.2. Cross-Region Comparison

Figure S8 shows how net leakage is positively correlated with net imports into the region that implements the SCC pricing policy, as imported power from transmission-connected regions with less stringent policy becomes more cost competitive in regulated regions. This result aligns with the NW-Central observation that the electricity trade channel is an important leakage pathway, partially offsetting emissions reductions in the regulated region. The figure also illustrates how cumulative leakage increases over time for most of the study regions owing to rising SCC prices.3

3 This correlation between leakage and trade holds in alternate SCC price trajectories and specifications of leakage metrics (i.e., whether annual or cumulative leakage is used).
Figure S8. Cumulative leakage and annual net imports under unilateral CO₂ pricing scenarios for all 14 regions and SCCM pricing (the size of the bubble is proportional to the level of emissions reduction in the SCC region).

Figure S9 illustrates regional variation in cumulative leakage for a particular SCC price path, as well as across region variation in the sensitivity of leakage to a change in the SCC price path. Leakage increases with larger SCC price trajectories in some cases, but not all. The extent of this increase is region-specific and depends on the marginal generating unit in-region and out-of-region, relative prices, transmission linkages, etc. Some regions (e.g., New England) reverse the sign of leakage between the low and higher SCC prices, while other regions (e.g., California) are relatively high for all scenarios.
In addition to unilateral regional SCC pricing, we investigate a national SCC pricing scenario applied to the entire U.S. power sector to explore leakage through fuel markets into other economic sectors, outside of the electric sector. Figure S10 shows estimated leakage outside of the U.S. power sector for the three SCC pricing trajectories. Leakage is initially negative, due to higher fuel prices; however, leakage becomes positive over time as the non-electric sectors switch fuels away from electricity. By 2040, there is small, but positive cumulative leakage (1–3%). This result is a function of the assumed price responsiveness of future fuel markets to changes in relative fuel prices. This is a topic worthy of additional analysis.
Figure S10. Annual (graph) and cumulative (table) non-electric CO₂ leakage through 2025 and 2040 (%) with national SCC pricing

Figure S11 compares the cumulative electric sector capacity additions through 2050 in the NW-Central region when SCC pricing is implemented in the NW-Central versus nationally. For NW-Central SCC pricing, in-region capacity investments decrease relative to the reference case, which indicates the degree to which imports become a more cost-effective electricity supply resource. With national SCC pricing, we find an increase in NW-Central capacity additions and consequently higher costs for the NW-Central region. In the national SCC cases, imports from neighbors are less attractive because their CO₂ is priced as well. This sensitivity underscores that policies in neighboring regions materially impact economic and environmental outcomes and should be considered in policy analysis.
Finally, we consider two additional sensitivities independently—SCC pricing with no new transmission and SCC pricing with inelastic (i.e., unresponsive to price changes) electricity demand. Figure S12 shows cumulative leakage outputs from these sensitivities for our five focus regions under unilateral SCCH regional pricing. First, restricting transmission capacity additions leads to lower leakage if the SCC region is already relatively isolated (e.g., Texas). However, in regions that are already well-connected with adjacent unregulated regions (e.g., NW-Central, California), leakage increases slightly. Lower in-region CO₂ reductions occur in these regions due to increased gas use, but out-of-region emissions also increase with increased SCC region imports on existing transmission capacity. Note that constraining transmission additions not only limits imports into the SCC pricing region, but also limits exports from the SCC pricing region, which, among other things, we find is part of the value of regulated region renewables. Second, leakage increases when electricity demand is not price-responsive (*ceteris paribus*). Inelastic demand results in even higher electricity prices as consumer demand reductions are not moderating rising prices, and as a result, there is increased incentives for electricity imports.

**Figure S11.** Cumulative NW-Central region capacity additions by 2050 with SCC power sector pricing in the NW-Central region only (“NWC Only”) and in all U.S. regions (“US”)
Figure S12. Cumulative leakage to 2040 (%) for five select regions with SCCH pricing with core scenario set-up ("SCCH") and sensitivities for no new transmission and inelastic demand.
References

Anthoff D, Rose S, Tol R S, and Waldhoff S T 2011 The Time Evolution of the Social Cost of Carbon: An Application of FUND. Economics Discussion Paper 2011-44.

Babiker M H 2005 Climate change policy, market structure, and carbon leakage Journal of International Economics 65(2):421–445.

Blanford G J, Merrick J H, Bistline J E, Young D 2016 Simulating annual variation in load, wind, and solar by representative hour selection. EPRI, Palo Alto, CA. EPRI Technical Update 3002008653.

Blanford G J, Merrick J H, and Young D 2014 A clean energy standard analysis with the US-REGEN model. The Energy Journal 35(1):137–164.

Böhringer C, Balisteri E J, and Rutherford T F 2012 The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29) Energy Economics 34:597–5110.

Bushnell J and Chen Y 2012 Allocation and leakage in regional cap-and-trade markets for CO₂ Resource and Energy Economics 34(4):647–668.

Caron J, Rausch S, and Winchester N 2015 Leakage from sub-national climate policy: The case of California’s cap-and-trade program The Energy Journal 36(2):167–190.

Chen Y 2009 Does a regional greenhouse gas policy make sense? A case study of carbon leakage and emissions spillover Energy Economics 31(5):667–675.

Cullenward D 2014 Leakage in California’s carbon market The Electricity Journal 27(9):36–48.

Electric Power Research Institute 2017 US-REGEN Model Documentation. EPRI, Palo Alto, CA. EPRI Technical Update 3002010956.

Eichner T and Pethig R 2015 Unilateral consumption-based carbon taxes and negative leakage Resource and Energy Economics 40:127–142.

Fowlie M L 2009 Incomplete environmental regulation, imperfect competition, and emissions leakage American Economic Journal: Economic Policy 1(2):72–112.

Goulder L H and Stavins R N 2011 Challenges from state-federal interactions in US climate change policy American Economic Review 101(3):253–257.

Kahn M E and Mansur E T 2013 Do local energy prices and regulation affect the geographic concentration of employment? Journal of Public Economics 101:105–114.

Rose S K, Diaz D, and Blanford G 2017. Understanding the Social Cost of Carbon: A Model Diagnostic and Inter-Comparison Study, Climate Change Economics 8(2).

Rose S, Turner D, Blanford G, Bistline J, de la Chesnaye F, and Wilson T 2014 Understanding the Social Cost of Carbon: A Technical Assessment. EPRI, Palo Alto, CA. Technical Update 3002004657.
Sauma E 2012 The impact of transmission constraints on the emissions leakage under cap-and-trade program *Energy Policy* **51**:164–171.

Winchester N and Rausch S 2013 A numerical investigation of the potential for negative emissions leakage *American Economic Review* **103**(3):320–325(6).

United States Government Interagency Working Group (2016) *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, Interagency Working Group on Social Cost of Greenhouse Gases, August.