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Social cost of carbon pricing of power sector CO_2: accounting for leakage and other social implications from subnational policies

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Abstract

In environments where climate policy has partial coverage or unequal participation, carbon dioxide (CO_2) emissions or economic activity may shift to locations and sectors where emissions are unregulated. This is referred to as leakage. Leakage can offset or augment emissions reductions associated with a policy, which has important environmental and economic implications. Although leakage has been studied at national levels, analysis of leakage for subnational policies is limited. This is despite greater market integration and many existing state and regional environmental regulations in the US. This study explores leakage potential, net emissions changes, and other social implications in the US energy system with regionally differentiated pricing of power sector CO_2 emissions. We undertake an economic analysis using EPRI's US-REGEN model, where power sector CO_2 emissions are priced in individual US regions with a range of social cost of carbon (SCC) values. SCC estimates are being considered by policy-makers for valuing potential societal damages from CO_2 emissions. In this study, we evaluate the emissions implications within the SCC pricing region, within the power sector outside the SCC region, and outside the power sector (i.e. in the rest of the energy system). Results indicate that CO_2 leakage is possible within and outside the electric sector, ranging from negative 70% to over 80% in our scenarios, with primarily positive leakage outcomes. Typically ignored in policy analysis, leakage would affect CO_2 reduction benefits. We also observe other potential societal effects within and across regions, such as higher electricity prices, changes in power sector investments, and overall consumption losses. Efforts to reduce leakage, such as constraining power imports into the SCC pricing region likely reduce leakage, but could also result in lower net emissions reductions, as well as larger price increases. Thus, it is important to look beyond leakage and consider a broader set of environmental and economic metrics. Leakage rates, net emissions outcomes, electricity price changes, fuel market effects, and macroeconomic costs vary by region of the country, time, policy stringency, policy design (e.g. leakage mitigation provisions), policy environment in neighboring regions, and price responsiveness of demand.

1. Introduction

With uncertainty about United States (US) federal action on climate change, states and other subnational jurisdictions have become laboratories for policy experimentation. There are many implementation approaches (e.g. market-based instruments, portfolio standards and subsidies to promote innovation and commercialization of low-carbon technologies, performance mandates) and many rationales (e.g. emissions reductions, economic growth, job creation, symbolic activities) for pursuing unilateral climate policy and technology R&D. Given the proliferation of regional policies, it becomes important to evaluate their economic and environmental consequences, especially if the intent is to determine the most effective policies with satisfactory levels of public acceptance within existing implementation authorities.

Pricing carbon dioxide (CO_2) emissions is a potential policy alternative, with indirect and direct means for valuing CO_2 emissions reductions in economic decisions. Taxing emissions is a form of the latter, with some considering setting the tax according to the social cost of carbon (SCC). SCC values are estimates of the societal damages associated with emitting an additional unit of CO_2, and federal and state regulators have adopted or are considering using SCC estimates (Rose and Bistline 2016). For instance, the Minnesota Public Utilities Commission considered SCCs in updating its CO_2 externalities pricing in power sector resource planning.[3]

In evaluating the implications of such proposals, regulatory impact analysis should account for benefits and costs in all segments of the economy and not merely the regulated one, especially for policies with incomplete coverage across sectors, sources, or regions. Policy-induced changes of this type are characterized as "leakage," since they impact net effectiveness.[4] Market linkages make leakage a potential issue for regionally differentiated policies, since policy design choices in one jurisdiction influence economic conditions and environmental integrity of the system as a whole. An area where leakage is a significant concern is regional[5] energy and climate policy. Emissions leakage is one issue. Regional policies may also have broader environmental implications as well as other social consequences relevant to policy discourse. These include economic and infrastructure implications within and across regions.

Although subnational climate-related policies have received greater policy focus in light of stalled federal measures, few studies in the literature investigate the potential implications of regional energy and climate policies. Leakage channels are often difficult to identify and quantify, but can be of first-order importance in evaluating impacts of policy alternatives (Caron *et al* 2015). Current policy applications and regulatory practices, however, typically account for changes only in the regulated segment of the economy. For instance, despite its potential significance, emissions leakage is only mentioned in a small fraction (less than 5%) of current US regulatory applications of the social cost of carbon (SCC), and none of these calculations were adjusted in response to these observations (Rose and Bistline 2016). As such, estimates of the climate benefits of emissions reductions will be biased high when, all else equal, there is positive leakage and that leakage is ignored, which is common in regulatory and subnational policy analyses. If leakage (positive or negative) is likely, it needs to be considered for proper climate and net benefits estimation.

To date, empirical and modeling studies of leakage have typically concentrated on national climate policies and have focused on quantifying leakage mechanisms, rates, and trade impacts (e.g. Böhringer *et al* 2012, Babiker 2005). The limited literature on US leakage and regional externality-correcting policies have focused on existing policies in California and the Regional Greenhouse Gas Initiative (RGGI) states (Caron *et al* 2015, Fowlie 2009, Chen 2009). 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 (for further discussion, see section 1 of the supplementary information, SI, available at stacks.iop.org/ERL/13/014027/mmedia). These studies suggest that unilateral subnational policies may lead to leakage rates between 9% and 57% depending on the region and policy provisions. National leakage rates tend to be lower than those for subnational policies, with rates commonly between 0% and 20% (Böhringer *et al* 2012), due to greater market integration at state and regional levels.

More holistic consideration of environmental and economic consequences would facilitate identification of a broader set of metrics and tradeoffs important to policy decision-making. In this paper, we investigate leakage potential and other social effects under regional power sector CO_2 pricing using an integrated modeling framework with detailed US electric sector investment and operations decisions embedded within changing US energy markets and overall economy. This analysis is the first to apply a linked electric sector and computable general equilibrium (CGE) model to evaluate net emissions changes in power markets and the energy system under regional SCC values. Specifically, the analysis is the first to evaluate emissions implications of unilateral policies for 14 different subnational US geographical areas, including emissions changes within the regulated region, across other regions, and across other sectors of the economy. A final contribution is to investigate changes in emissions across a range of prospective policies, which provides insight into the relationship between leakage and regulatory stringency. Note that, although using alternate SCC estimates in this analysis provides sensitivities representing policy

[3] See the July 27, 2017 utility commission decision regarding revised CO_2 externalities pricing (https://mn.gov/puc/). See also *In the Matter of the Further Investigation into Environmental and Socioeconomic Costs Under Minnesota Statutes § 216B.2422, Subdivision 3*, Administrative Law Judge's Findings of Fact, Conclusions, and Recommendations: Carbon Dioxide Values. State of Minnesota, Office of Administrative Hearings, For the Public Utilities Commission. OAH 80-2500-31888. MPUC E-999/CI-14-643. The judge's decision not only recommended using SCC values, but also recommended investigating how to measure and consider potential emissions leakage.

[4] Leakage refers to any regulatory-induced shift in production (and consequently emissions) toward uncovered or less stringently regulated sources.

[5] Here, 'regional' describes any subnational regulation or policy, which could be implemented at regional, state, or local levels.

stringency, leakage and other societal implications do not depend on whether the CO_2 price equals the SCC. Overall, our results generalize to CO_2 pricing of electric sector emissions of any kind.

These experiments illustrate how leakage, both positive and negative, is likely under unilateral regulations and how leakage rates can be non-trivial fractions of the intended emissions reductions. However, our findings also reveal trade-offs in policy design between economic and environmental outcomes, with economic effects spilling over into neighboring regions. We also find that the leakage metric provides an incomplete environmental picture that is not representative of overall emissions. This is especially important as provisions designed to limit leakage rates may result in a decrease in net emissions reductions. The next section discusses our analytical approach. Our results are presented in the third section, where we begin with a detailed evaluation of SCC pricing of power sector CO_2 in a single US region, followed by a cross-regional comparison of implications. We conclude with summary remarks and discussion.

2. Methods

2.1. Model overview

This analysis uses the dynamic integrated version of the US Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model, with a multi-region dynamic CGE model of the economy iterating with a detailed electric sector model (EPRI 2017, Blanford *et al* 2014). The detailed electric sector model solves an intertemporal capacity planning and dispatch problem that simultaneously optimizes investments (including new capacity, retrofits, and retirements), operational choices, and interregional transmission. The detailed intra-annual temporal resolution and regional heterogeneity are critical for representing power system operations and trade, as many other models do not represent endogenous import and export decisions (Santen *et al* 2017). The electric sector model examines simultaneous changes in power plant dispatch and investments across scenarios, including where to locate these new investments on a regional basis. The bottom-up electric sector model dynamically iterates and converges with a top-down CGE model of the economy, which represents energy markets as well as residential, commercial, industrial, transportation, and refining sectors, and the greenhouse gas emissions resulting from activity levels and fuel use. See SI section 2 for a detailed discussion of model features, regional disaggregation, and assumptions relevant to this analysis.

2.2. Scenarios and SCC price paths

The analysis explores potential leakage and economic effects using a range of SCC pricing scenarios. The scenarios apply SCC trajectories as prices (taxes) on the power sector CO_2 emissions of individual regions.

Table 1. Summary of core SCC pricing scenarios.

Region	SCC trajectory	Import constraint
Region X	None	No
Region X	SCCL (lower)	No
Region X	SCCM (middle)	No
Region X	SCCH (higher)	No
Region X	SCCL	Yes
Region X	SCCM	Yes
Region X	SCCH	Yes

The analysis focuses on three SCC price trajectories to investigate how SCC pricing levels could affect results.[6] Given the issues identified by Rose *et al* (2014, 2017) associated with a multi-model approach to SCC estimation, we use the SCC trajectories from a single integrated assessment model, FUND, instead of the values developed by a US Government Interagency Working Group (IWG).[7] Specifically, our three SCC pathways (shown in SI figure S2) are from Anthoff *et al* (2011) and reflect scientific uncertainty about the sensitivity of the climate system. The start year for SCC pricing (in \$ per ton CO_2) in our low (SCCL), medium (SCCM), and high (SCCH) scenarios is 2020, with values differing from the start and increasing and diverging over time. Given the possibility of CO_2 leakage across regional borders, we also analyze a simple leakage mitigation provision to evaluate the effectiveness and broader implications of such mechanisms. In these cases, we run an 'import constraint' sensitivity that prohibits electricity imports into the SCC pricing region above reference import levels (i.e. levels when there is no SCC pricing). Table 1 summarizes the different core scenario permutations considered in the analysis, which are applied to each region individually.

In addition to our core scenarios, we run sensitivities, varying electricity demand price responsiveness, constraining power sector transformations (in particular, transmission additions), and comparing national and regional electric-sector SCC pricing. Our

[6] Note that these SCC trajectories are used merely to analyze the impact of unilateral subnational policies on leakage and other social implications. We do not suggest that these values represent a 'best estimate' of the social cost of carbon, especially given the many technical issues associated with SCC estimation (Rose *et al* 2014, 2017, NAS 2017).

[7] Rose *et al* (2014, 2017, NAS 2017) identified consistency, comparability, uncertainty, and robustness issues with the IWG approach utilizing three models, and recommended consideration of an alternative approach. NAS (2017) also found the multi-model approach problematic and recommended an alternative framework. Note that the IWG values were withdrawn from federal regulatory use and replaced with alternative guidance for monetizing changes in greenhouse gases by President Trump (Executive Order 'Promoting Energy Independence and Economic Growth,' March 28, 2017). The IWG SCC estimates, modeling, and their issues, however, continue to be relevant as the US Government considers alternatives, and states, countries, other decision applications, and academics consider options for decision-making and as benchmarks (for examples, see Rose and Bistline 2016).

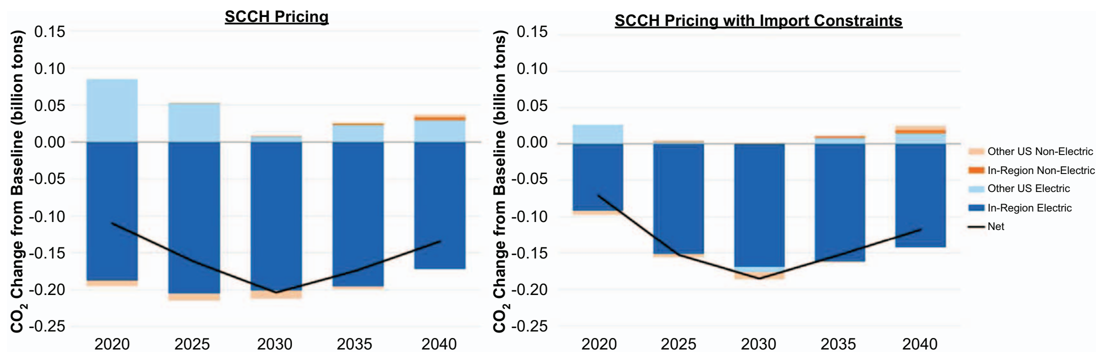

Figure 1. CO_2 change by sector from the reference (i.e. no-policy reference) under the SCCH pricing scenario for the NW-Central region without (left) and with (right) import constraints.

analysis does not model the potential for positive spillovers related to technology or policy diffusion, which are outside of the scope of this work.

2.3. Defining leakage

This analysis presents CO_2 emissions leakage over time through the metric of cumulative leakage, which is specified through a particular model period T. A cumulative leakage metric can aggregate temporal effects of policies and can give a more robust and comprehensive characterization of net environmental impacts than an annual leakage value for a specific year. Cumulative values are also more relevant to a key climate change metric—global mean temperature. We define this cumulative leakage rate through the following equation:

$$\lambda_T = -\frac{\Sigma_{t=t_0}^{T}[\Delta_S^N + \Sigma_{r\neq S}(\Delta_r^E + \Delta_r^N)]}{\Sigma_{t=t_0}^{T}[\Delta_S^E]} \quad (1)$$

where λ_T is the cumulative leakage rate (%) through time T, $\Delta_r{}^i$ is the difference in emissions between the SCC policy and no-policy scenarios for region r in the electric power sector E and non-electric sectors N (with s the treatment region where the SCC prices are imposed), t is the set of all model time periods, and t_0 is the first period when the SCC is imposed (2020). Essentially, the leakage rate is the change in emissions in all sectors and regions outside of the regulated area (in this case, the SCC region power sector) divided by the expected decrease in regulated emissions. This analysis follows convention in the literature that an increase in unregulated emissions is referred to as 'leakage,' and a decrease is referred to as 'negative leakage.' Note that leakage rates measure policy-induced changes relative to the baseline when the unilateral policy is not pursued, which accounts for trends in both the regulated and unregulated segments of the economy. Leakage can occur when unregulated activity increases fossil fuel use in response to the policy elsewhere. Negative leakage can occur when fuel market changes in the controlled region lead to price increases in unregulated regions, which may lead to lower consumption, factor migration, or shifts in the energy mix that ultimately lead to lower emissions than the counterfactual in which the neighboring region did not implement the unilateral policy (Caron *et al* 2015, Eichner and Pethig 2015, Baylis *et al* 2014).

3. Results

To provide intuition into the mechanisms for leakage, overall emissions changes, and economic outcomes, we begin with an intimate exploration of results for a single region, Northwest Central (NW-Central).[8] The subsequent section compares results across model regions (i.e. with SCC pricing applied one region at a time) to understand how region-specific factors could influence qualitative and quantitative insights.

3.1. Northwest-central region results

When the SCC trajectories are applied to the power sector in the NW-Central region only, we find CO_2 reductions, as well as leakage (i.e. CO_2 changes outside of the NW-Central power sector). The left-hand panel in figure 1 shows the high SCC policy (SCCH) lowering CO_2 emissions in the NW-Central power sector (dark blue), and power sector emissions in other regions (light blue) simultaneously increasing. Emissions changes outside the electric sector, however, are relatively small—in both the NW-Central (dark orange) and other regions (light orange). Overall, due to leakage, net emissions reductions (black line) are less than the emissions reductions from the NW-Central power sector.

The primary channel for the observed leakage is through electricity trade with other regions. Emissions increase in the electric sector outside the NW-Central due to increases in power exports to the NW-Central, as SCC pricing improves the competitiveness of imported power within NW-Central. For instance, imported power increases from 0.6%–5.3% of in-region electricity consumption in 2025 in the scenario associated with figure 1. On the other hand, changes in fuel con-

[8] As shown in figure S1, the NW-Central region includes Minnesota, Iowa, Missouri, North and South Dakota, Nebraska, and Kansas.

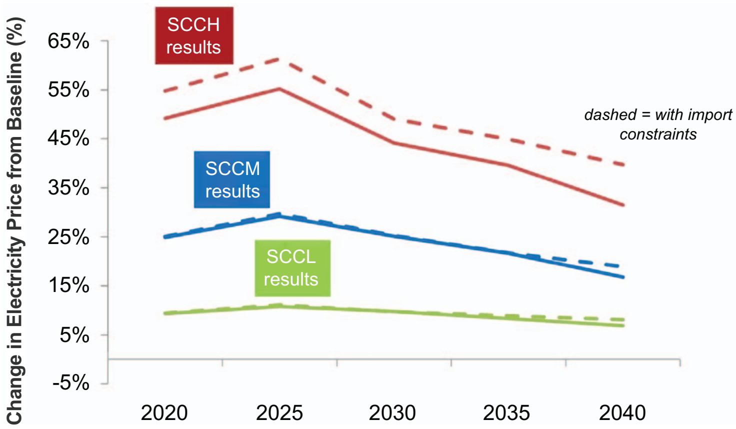

Figure 2. Percent change in electricity price from the reference (i.e. no climate policy) scenario in the NW-Central region without and with import constraints (solid and dashed lines, respectively).

sumption driven by changes in relative fuel prices (i.e. fuel market leakage) are modest.[9]

When we constrain NW-Central power imports to their no-policy levels, emissions leakage is lower (figure 1, right panel). Specifically, we see smaller increases in electric sector emissions outside NW-Central. However, we also find that the overall environmental benefits—net reductions in CO_2 emissions—are reduced. In particular, constraining imports results in smaller NW-Central power sector CO_2 reductions due to a greater reliance on in-region resources rather than electricity imports. This includes greater generation with existing coal and gas units compared to the unconstrained import SCC pricing case (figure S6).

Across SCC pricing scenarios (figure S3), we find that leakage increases with higher (SCCM or SCCH) versus lower SCC prices (SCCL), but it is non-monotonic. In other words, higher SCCs do not always increase the leakage rate. We do, however, find that higher SCCs produce larger net CO_2 reductions. Meanwhile, we find that important constraints reduce leakage for all SCC price trajectories, with some cases also having the unintended consequences of reducing net emissions reductions. Overall, these findings suggest that leakage is relevant, but focusing on leakage rates alone could yield an incomplete picture of the environmental impacts of a policy, and net reductions should also be considered.

Figure 2 shows the percentage change in NW-Central electricity prices for the three SCC trajectories, with and without import constraints. Price increases are larger for higher SCC trajectories (as high as 60% in 2025) and decrease over time as system capacity adjusts to the policy shock. Price increases are even greater when imports are constrained, which indicates the important economic role of electricity imports in helping moderate the increased cost of service. This effect is more pronounced when there are higher SCC prices.

The unilateral policy also impacts prices in neighboring regions (figure S4). The most significant price changes occur in the SCC pricing region (NW-Central); however, we also observe price changes in neighboring regions that are direct electricity trading partners, with price increases or decreases depending on regional conditions over time.[10]

In addition to prices, we are also interested in other potential economic effects. Changes in electric sector costs and macroeconomic consumption are useful indicators of the potential broader effects on society. Pricing CO_2 can change the composition of electricity production costs as well as total costs. For instance, we find NW-Central total electric sector costs increasing with SCC pricing, and by greater amounts the higher the SCC level (figure S5). Investment, regulatory, and import purchase costs generally increase, while fuel costs, operating costs, and export sales decrease. With import constraints, we find a different distribution of cost changes—with greater in-region investments and reduced expenditures on electricity imports, even below reference levels due to changes in the economics driving capacity investments and hourly dispatch, including greater renewables capacity that can result in the displacement of reference imports in some load segments (SI section 3.1).

Macroeconomic consumption, on the other hand, is a more comprehensive metric for societal economic impacts that reflects effects after they ripple

[9] The 'trade channel' for leakage refers to emissions changes induced by relative price differences as power production shifts between regions, in many cases with generation moving away from the constrained region to unconstrained ones (i.e. through cross-border transactions).

[10] Price decreases in neighboring regions can occur during periods when power exports from the SCC pricing region are economically competitive. This can happen, for instance, when there are cross-region differences in load profiles and renewables generation.

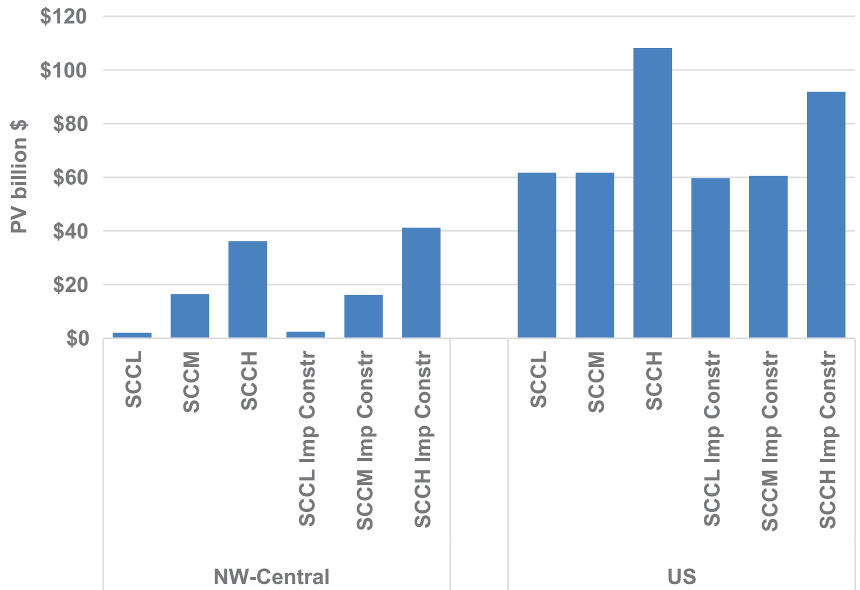

Figure 3. Macroeconomic consumption losses for the NW-Central region and the entire US (billion $ present value from 2010–2050) with NW-Central SCC pricing policies.

through the rest of the economy.[11] Figure 3 shows that NW-Central net present value consumption losses increase significantly with SCC level, and that adding import constraints could make the losses even larger. The figure also illustrates the potential for consumption losses beyond NW-Central, with total US losses greater than those in NW-Central. Other regions experience changes in the relative prices of fuels and, depending on net trade positions for electricity, may build considerably more generation capacity than would be cost-effective in a no-policy counterfactual.[12] Thus, the welfare impacts of the regional SCC policy extend beyond the regulated region.

3.2. Cross-region comparison

Regions differ in their electricity generation mix, resource base, market conditions, and transmission infrastructure. Examining unilateral SCC pricing across different regions (applied in each region separately) provides insights about which impacts are robust across SCC price paths and regions and which reveal important differences.

Overall, the magnitude and sign of cumulative leakage rates through 2040 vary by region and SCC price path, spannng from negative 70% to positive 80%, with primarily positive leakage outcomes (figure 4).[13] Many of these rates are higher than the reported values in the literature for national policies (Caron *et al* 2015).[14] The results from these experiments also confirm our NW-Central observation that leakage is positively correlated with net imports into the SCC pricing region (SI figure S8), as imported power from transmission-connected regions with less stringent policies becomes more cost competitive in regulated regions.

Two factors are defining leakage outcomes: (i) relative regional electricity prices (at the load segment level), and (ii) relative regional CO_2 intensities of power generation (CO_2 per unit output). The import volume and electricity price increases are larger if the SCC region has a higher reference power sector CO_2 intensity. This feature and the CO_2 intensity of imported power are key determinants of power sector leakage. Other elements also contribute to region-specific variation in the leakage rate, including own-price elasticities, transmission linkages, and a region's net trade position in the reference case. We find that the relative importance of these factors varies by region and interact in complex ways. Ultimately, the differences in hourly market-clearing electricity prices across regions (and their marginal CO_2 emissions) determine emissions leakage.

Figure 4 also shows the relationship between cumulative leakage to 2040 and electricity price changes with the unilateral SCC policies. For the low (SCCL) trajectory, there is significant variation across regions in

[11] For this analysis, all revenues from SCC pricing are distributed on a lump sum basis to households. Economic impacts would likely be lower if revenues are recycled through reductions in existing distortionary taxes (Goulder 2013).

[12] National totals obscure significant regional variation in economic outcomes, as some regions bear more significant consumption losses than others.

[13] The limited number of negative leakage results occur in the least stringent policy scenarios in regions where non-electric fuel market pricing effects dominate, which leads to lower non-electric fuel consumption and emissions in neighboring regions.

[14] Leakage rates for national policies in the literature are typically between 0 and 20% (Böhringer *et al* 2012) but vary significantly based on the stringency, context, and enforcement provisions.

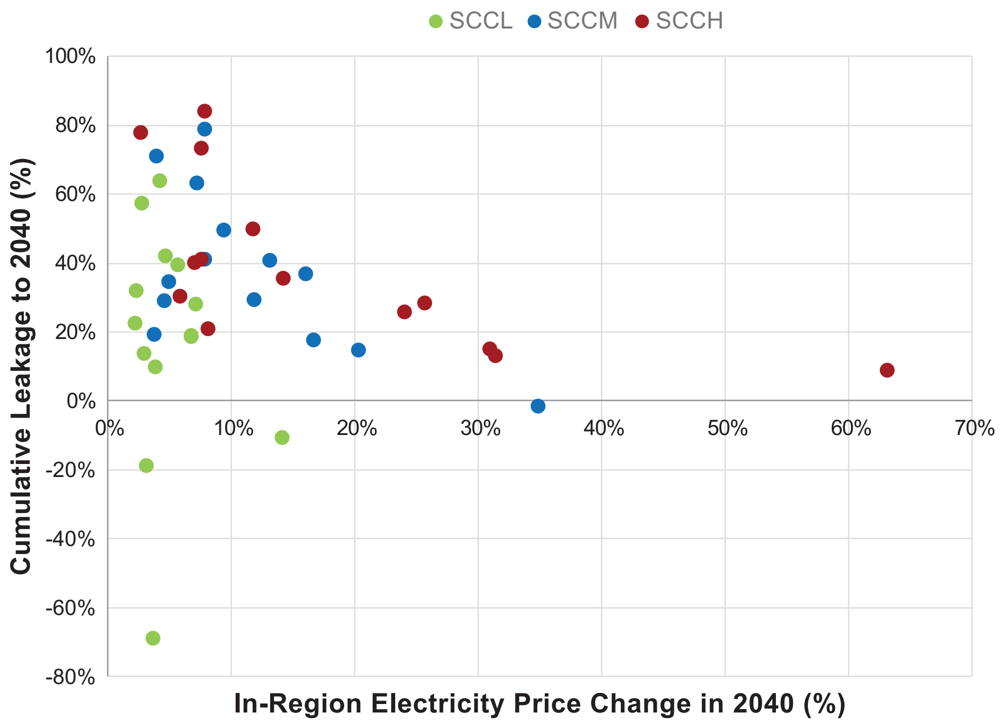

Figure 4. Regional cumulative CO_2 leakage to 2040 (%) and electricity price changes (%) in 2040 with region-specific SCC pricing and no import constraints.

the leakage dimension, but the electricity price changes are relatively similar. For the SCCM and SCCH trajectories, there is more variation in both dimensions. Overall, we observe movement up and to the right as the SCC increases, indicating that higher SCCs suggest greater leakage and price increases. Note that while we find the possibility of negative leakage for some regions with lower SCC prices, we observe only positive leakage with the higher SCCH.

Looking at individual region responses, we find that there is substantial variation across regions in the sensitivity of leakage to the SCC price path (SI figure S9). Leakage increases with larger SCC price trajectories in many regions, but not all. The extent of the increase is region-specific and depends on the marginal generating unit in-region and out-of-region, transmission linkages, and other factors.[15] Negative leakage may occur when unregulated neighboring regions have lower emissions intensities than the regulated region, which might be the case for RGGI states in the Northeastern US (Fell and Maniloff 2015). Meanwhile, electricity price changes generally increase with the SCC pricing level as it becomes increasingly more expensive to provide electricity within the regulated region. Note also that the near-term electricity price changes in each region (percentage changes in 2025) are typically larger, sometimes much larger (recall figure 2), given the limited time to adjust to the SCC pricing.

[15] See SI section 3.2 for a more detailed discussion of the drivers leading to region-specific variation across leakage rates.

We next evaluate the potential implications of regional leakage reduction policies on environmental and economic outcomes using five heterogeneous focus regions. The focus regions simply allow for more parsimonious figures. The top panel in figure 5 presents the regional leakage and electricity price changes for unilateral SCCH pricing without and with electricity import constraints. As with the NW-Central case, constraining imports into the SCC region decreases the leakage rate, and increases the electricity price. The result is robust across all five regions, but the magnitude of the effect varies.

The bottom panel of figure 5 shows the relationship between cumulative leakage rates and cumulative US net CO_2 reductions (i.e. net reductions nationwide). For four of the focus regions, implementing power import constraints to reduce leakage also lowers overall emissions reductions.

Together, our cross-region results confirm that leakage is likely with subnational policies, and that it can be significant. They also confirm that focusing on leakage alone ignores tradeoffs between economic and environmental outcomes. Furthermore, the leakage metric provides an incomplete environmental portrait of emissions, which is especially important given how provisions designed to limit leakage rates may counterintuitively result in a decrease in emissions reductions, as well as an increase in cost. Together, these leakage management results raise questions about the economic efficiency, distributional impacts, and environmental efficacy of such policies.

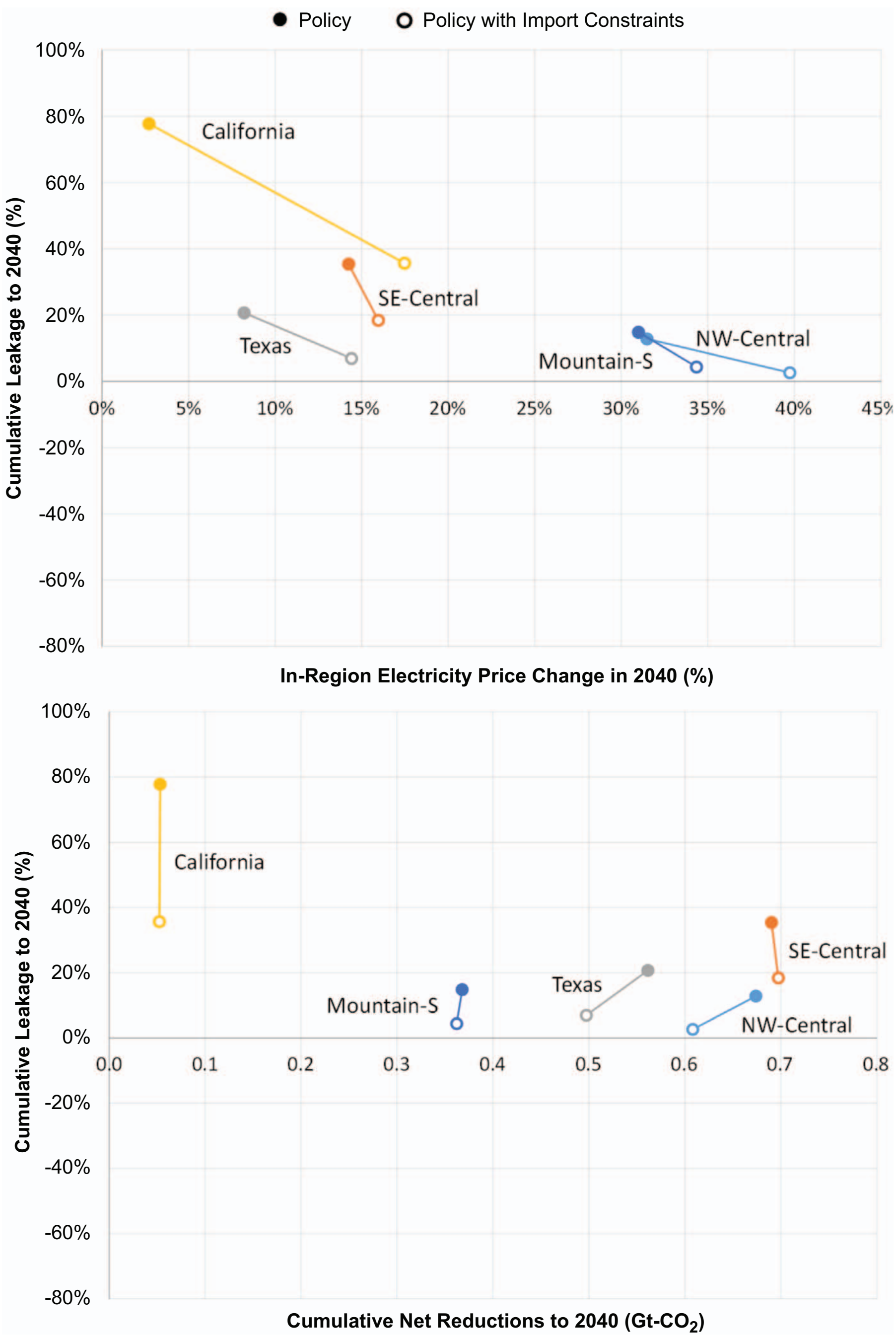

Figure 5. 2040 regional cumulative leakage and electricity price changes (top) and cumulative leakage and net emissions reductions (bottom) with SCCH and with and without power import constraints.

Overall, our cross-region comparison implies that the qualitative leakage and economic consequences found for the NW-Central region (section 3.1) are robust across different regional contexts, but with variation in the quantitative outcomes. These results also illustrate the importance of modeling a broader geographic scope, regional heterogeneity, and general equilibrium effects in order to evaluate electric-sector, fuel market, and macroeconomic impacts of subnational policies.

3.3. Other sensitivities

In the SI (section 3.3), we present additional results for sensitivities involving national power sector SCC pricing, new transmission additions, and electricity demand response. With the national SCC pricing scenarios, we further explore fuel market leakage into other economic sectors, and find small, but positive, cumulative leakage (1%–3%). From these and other results, we also conclude that policies in neighboring regions should be considered in policy analysis, as they can materially impact electric sector generation capacity decisions, in addition to the economic and environmental outcomes. Lastly, we find the potential for slightly higher leakage rates when there are either constraints on the building of new transmission, or less price responsive electricity demand, though magnitudes and signs vary by region. These findings are explained in greater detail in SI section 3.3.

4. Conclusion

Subnational jurisdictions committed to reducing greenhouse gas emissions need to quantitatively evaluate the risk of leakage and other social implications from unilateral policies. This analysis illustrates a rigorous framework for assessment in the context of subnational regionally differentiated pricing of power sector CO_2 emissions. We demonstrate that emissions leakage and economic implications are likely and potentially non-trivial.

Leakage rates vary by region, from negative 70% to over 80% depending on region and regulatory stringency, with generally positive leakage and rates higher than those found for national policies (which are commonly between 0% and 20%). For the heterogeneous subnational policies examined here, the trade channel for electricity was the primary mechanism for leakage, though fuel market leakage also occurred. Future work with more disaggregated model representations of industry would be valuable for quantifying uncertainty associated with non-electric-sector responses, especially for unilateral subnational policies that cover other sectors. In addition, we find the possibility of electric sector and macroeconomic costs within and beyond the regulated segment. Electricity price changes are likely within the jurisdiction implementing a unilateral policy and across neighboring regions. Electricity price changes vary by region, with a negative correlation between leakage rates and price increases and, like leakage, generally increase with the SCC pricing level. With electric sector investment and market implications extending beyond the regulated region, we find that the national macroeconomic costs of the regional policy are greater than the implementing region's costs.

Our modeling also demonstrates that leakage controls, like restricting electricity imports, can reduce leakage but may also reduce net emissions reductions. Leakage mitigation provisions lower emissions in unregulated regions but can raise emissions and costs in regulated regions. Constraining imports as a means of lowering leakage could also exacerbate price increases, especially with more stringent policies. Overall, it is important to look beyond leakage and consider a broader set of environmental and economic metrics.

These insights are consistent with Goodhart's law (Goodhart 1975), which suggests that when a specific metric (e.g. the leakage rate) becomes a regulatory target, its accuracy and benefits may be eroded by strategic manipulation, especially if this measure is an imperfect proxy for the desired outcome (e.g. net emissions reductions). An alternative approach to reduce leakage is for regions to coordinate and link climate policies.

Overall, we find that leakage is likely when there are differences in regional power sector policy stringencies (e.g. state externalities pricing, federal policy with differentiated state standards like the Obama Administration's Clean Power Plan). There are many dimensions of heterogeneity and variation, as environmental and economic effects are shown to vary by region, time, policy stringency, policy design (e.g. leakage mitigation provisions), policy environment in neighboring regions, and price responsiveness of demand. Evaluating and accounting for these effects will become increasingly important as states and other subnational jurisdictions enhance their climate and energy policy ambitions. Linked electricity and carbon markets are only as strong as their weakest link, which makes understanding and evaluating leakage risks important in ensuring that goals of emissions reductions do not become just reallocation.

Future work should evaluate the impact of other unilateral subnational policies on net emissions. The regional SCC pricing used here provides broadly applicable insights, but many proposed regulations entail unique provisions that require explicit modeling to evaluate potential impacts. Among other things, additional analysis should test alternate methods of mitigating leakage to understand tradeoffs in managing net emissions changes. Such work can also identify best practices for emissions monitoring and verification of unilateral policies to track how trade, emissions intensity, and other metrics respond to changes in relative prices. Since this work focuses on CO_2 emissions, future work should investigate net changes in local pollutants, which are also a policy focus but are imperfectly correlated with CO_2-emitting activities.

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