A Numerical Investigation of the Potential for Negative Emissions Leakage*

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IMPACTS OF UNILATERAL CLIMATE CHANGE POLICY[‡]

A Numerical Investigation of the Potential for Negative Emissions Leakage[†]

By Niven Winchester and Sebastian Rausch*

Leakage of greenhouse gas emissions—increased emissions in unconstrained regions due to regulations in other regions—undermines the effectiveness of sub-global climate regulations, reduces incentives for unilateral climate initiatives, and can result in distortionary trade measures (Winchester 2012). These concerns are expressed in measures to reduce leakage included in the EU Emissions Trading Scheme and draft legislation in the United States (the now defunct Waxman-Markey bill).

Two sources of leakage include changes in fossil fuel prices and trade flows (Carbone, Helm, and Rutherford 2009). Leakage via fossil-fuel price effects occurs when reduced energy demand in constrained regions decreases fuel prices and increases fuel use in unconstrained regions. Trade changes contribute to leakage when production increases in unconstrained regions as a result of increased exports to and reduced imports from constrained regions.

Opposing the conventional view, using a theoretical general equilibrium framework, Fullerton, Karney, and Baylis (2012)—henceforth FKB—show that emissions restrictions may decrease emissions elsewhere due to the abatement resource effect (ARE). The authors assert that negative leakage via the ARE occurs when increased demand for capital and labor to replace fossil fuels in carbon-taxed regions attracts factors of production from unregulated regions, which decreases unregulated output and ultimately emissions.[1]

Under the regional interpretation of the model used by FKB, two regions each produce a single good using a "clean'' input (a capital and labor composite) and carbon inputs (fossil fuels). The authors impose several general assumptions: (1) the two inputs are imperfect substitutes in production, (2) the two goods are imperfect substitutes in consumption, (3) the clean input is mobile across regions, and (4) the supply of the carbon input is perfectly elastic. As noted by the authors, due to the last assumption, the model excludes leakage due to changes in fossil fuel prices.

Using this framework, the authors relate the change in carbon inputs used in the unconstrained region to a terms-of-trade effect and an ARE. Under the terms-of-trade effect, the higher price of the good produced in the carbon-taxed region induces consumers to substitute toward the good from the other region, which has a positive impact on leakage. As noted earlier, the ARE reduces leakage. Net negative leakage is more likely (i) the lower the elasticity of

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[1] Several authors find negative leakage due to "non-standard'' model extensions, such as endogenous policy responses (see, for example, Copeland and Taylor 2005). We do not consider such extensions in our analysis.

substitution between the two goods in consumption (as this reduces the terms-of-trade effect), and (ii) the higher the elasticity of substitution between the clean and carbon inputs (as this increases the ARE).

In the remainder of this paper, we investigate the prospects for negative leakage in computable general equilibrium (CGE) models under alternative fossil fuel supply elasticity values and assumptions concerning capital and labor mobility. The next section presents results from a stylized numerical model, and Section II examines leakage using a multiregion CGE model of the US economy. Conclusions are summarized in the final section.

I. A Stylized Analysis

We begin by assessing the prospects for negative leakage in a stylized, easily tractable model. The model follows the regional interpretation of FKB's model, with two exceptions. First, to better reflect calibrated numerical general equilibrium models, we specify a home-bias in consumption rather than assuming that all consumers have the same utility function. Second, in addition to considering a case where the supply of carbon inputs is perfectly elastic, we consider several cases where this elasticity is less than infinity.

Our stylized model identifies two symmetric regions ("East" and "West") which each produce a single good. Based on (aggregated) data used for our calibrated general equilibrium model in Section II, we set cost shares for capital-labor (K) and carbon (C) inputs equal to, respectively, 0.98 and 0.02. Goods are traded across regions as imperfect substitutes. In each region, benchmark consumption shares for domestic and foreign goods are equal to, respectively, 0.85 and 0.15. C inputs are mobile across regions and we impose a constraint so that the equilibrium supply of C is equal to an exogenously-specified supply elasticity multiplied by the proportional change in the price of C. To maintain consistency with FKB, changes in the price of C are measured relative to the price of K in the East. The equations of the model are set out in the online Appendix, which also includes the source code for our numerical simulations.

We investigate the potential for negative leakage by imposing an *ad valorem* tax of 10 percent on carbon inputs in the West and solving the model for alternative values for the elasticity of carbon supply (η), and the elasticity of substitution between K and C in the west (σ^{Y}_{West}).[2] We implement separate sets of simulations for when K is (i) inter-regionally mobile, and (ii) region specific. In our core simulations, we set the elasticity of substitution in production in the East equal to one, and the elasticity of substitution in consumption (σ^{U}) equal to two in both regions.

Leakage will occur when the use of C changes in the East. Proportional changes in this variable when K is mobile across regions are presented in panel A of Figure 1. Consistent with the analytical results from FKB, there is positive leakage for low values of σ^{Y}_{West} and leakage decreases (i.e., there is less positive leakage or more negative leakage) as σ^{Y}_{West} increases.[3] Also as σ^{Y}_{West} increases, there is a larger decrease in the equilibrium quantity of C supplied to maintain a constant factor price, as illustrated in panel C of Figure 1.

When $\eta = 0$, the tax simply results in a reallocation of some C inputs from the West to the East and results in positive leakage. Increasing σ^{Y}_{West} allows greater substitution away from C in the West without inducing a larger decrease in supply of this factor, contrary to when $\eta = \infty$, so there is a positive relationship between σ^{Y}_{West} and leakage. For intermediate cases, $0 < \eta < \infty$, the tax reduces the equilibrium supply of C but by a smaller amount than when $\eta = \infty$. Consequently, leakage may be positive or negative. In our simulations, leakage is only negative when $\eta = \infty$.

Changes in the use of C in the East when K is region-specific are displayed in panel B of Figure 1. When $\eta = \infty$, as there is no change in relative input prices or K inputs in the East, production in this region is constant and leakage is zero for all values of σ^{Y}_{West}. When $\eta < \infty$, leakage in the mobile and immobile cases are similar. This is because, although reducing K mobility

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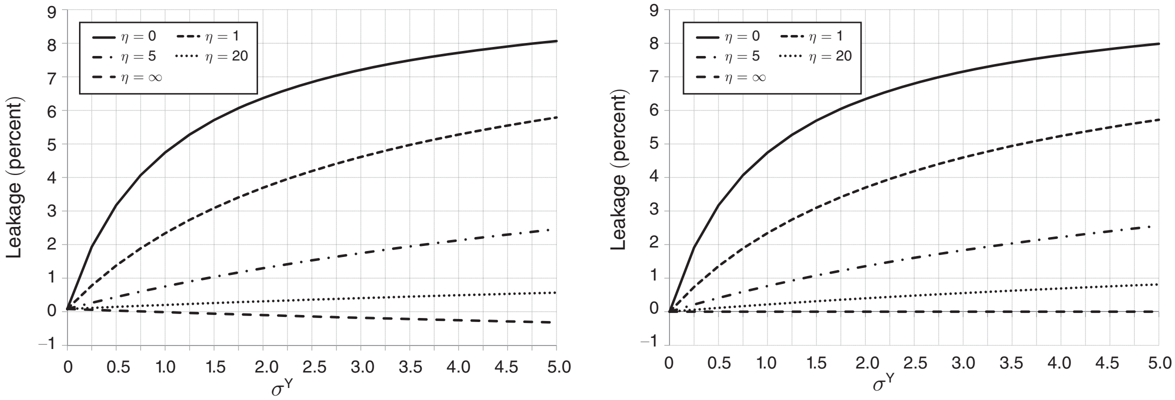
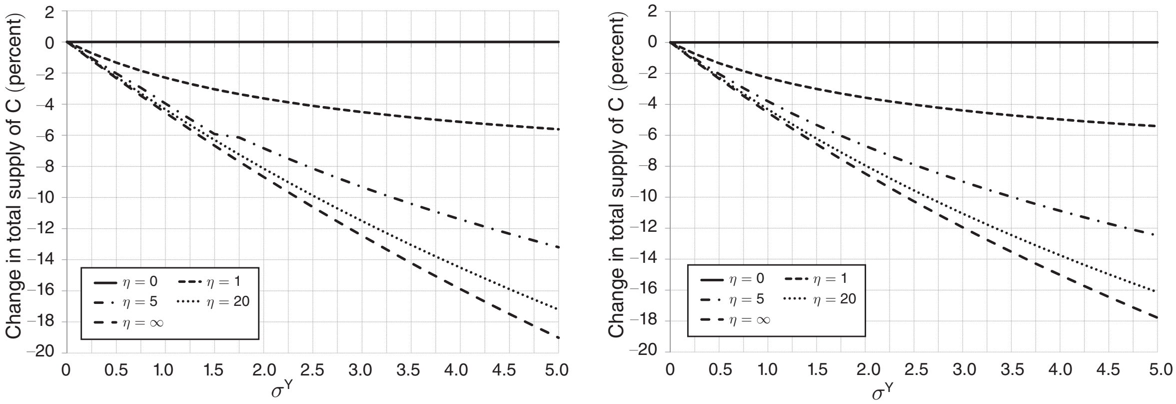
[2] Changing σ^{Y}_{West} is consistent with alternative representation of advanced, low-carbon technologies, such as renewable electricity generation and electricity from fossil fuels with carbon capture and storage. In unreported simulations, we also vary the substitution elasticities in both regions. Leakage is higher in these simulations than when we only change σ^{Y}_{West}, as increasing this elasticity in the East allows greater substitution toward fossil fuels in this region.

[3] In FKB's model, leakage is zero when $\sigma^{Y}_{West} = \sigma^{U}$. In our model, leakage is zero when $\sigma^{Y}_{West} < \sigma^{U}$ due to the home bias in consumption.


Panel A. Leakage in East, *K* mobile across regions.

Panel B. Leakage in East, *K* immobile across regions.


Panel C. Change in *C* supply, *K* mobile across regions.

Panel D. Change in *C* supply, *K* immobile across regions.

Figure 1. Leakage and Change in Supply of Carbon

reduces the ARE, it also reduces positive leakage via the trade channel (FKB 2012). In our simulations, allowing *K* mobility can increase or decrease leakage. The largest decreases in leakage due to mobility are observed for high values of η and σ^{Y}_{West}.

Comparing panels C and D of Figure 1 indicates that the decrease in the equilibrium supply of *C* is always larger when *K* is mobile than when this factor is region specific (except when $\eta = 0$). However, a larger decrease in the supply of *C* does not necessarily result in less leakage, as there is also greater displacement of *C* inputs in the West.

In sensitivity analyses, we concurrently vary η, σ^{Y}_{West}, and σ^{U}. Similar to FKB, there is more leakage for high values of σ^{U} than for low values of σ^{U}. The code to implement our sensitivity analyses is included in the online Appendix.

Overall, our results indicate the importance of the supply elasticity for *C* for observing negative leakage. The intuition behind this result is straightforward: negative leakage can only occur if the decrease in the equilibrium quantity of *C* supplied is greater than the reduction in *C* used in the West. Elasticities of substitution in the production and utility functions affect leakage as they influence the demand for *C*, which interacts with the supply elasticity to determine the equilibrium quantity of *C*.

II. Analysis Using a Large-Scale CGE Model

We investigate the potential for negative leakage in a large-scale model using a static version of the US Regional Economic Policy (USREP) model described by Rausch et al. (2010). The USREP model is multiregion, multi-sector calibrated general equilibrium model of the US economy with detailed representation of energy extraction and production that is benchmarked to 2006 data. The model is built on state-level input-output and trade data from IMPLAN (2008), and state-level data on energy balances and prices from EIA (2009). Using a model of subnational economies allows us to examine leakage and the ARE due to a sub-federal policy, which we prefer to a national climate initiative as capital and labor are more mobile within nations than across international borders.

We aggregate the data to identify five regions based on US Census Bureau groupings: West, Midwest, Northeast, South Atlantic, and South Central. Our sectoral aggregation includes five energy sectors (Coal, Crude oil, Gas, Refined oil, and Electricity) and five nonenergy sectors (Agriculture, Energy-intensive industry, Other industry, Transportation, and Services).

Crude oil is a homogenous commodity in the model. For other commodities, the model tracks bilateral trade among US regions and, following Armington (1969), assumes that imports are differentiated by region of origin. Operationalizing our import specification requires assigning values for elasticities of substitution between imports from different regions, and between aggregate imports and domestic production (trade elasticities), which we source from Beckman, Hertel, and Tyner (2011) and Caron, Rausch, and Winchester (2012).

We model the foreign sector by endowing each region with a exogenous quantity of foreign imports and requiring each region to produce a fixed quantity of international exports.[4] We also assume that all regions face a fixed price of crude oil. These assumptions eliminate leakage to foreign regions and allow us to focus on subnational leakage.

The model identifies five production factors: capital, labor, and sector-specific resources for Coal, Crude oil, and Gas. Production in each sector combines intermediate inputs and factors of production using nested constant elasticity of substitution (CES) functions. The utility function for each region is also a series of nested CES functions of commodities entering final demand. Key drivers of abatement possibilities include trade elasticities and the elasticity of substitution between aggregate energy and capital-labor (σ^Y) in production, especially in the electricity sector.

Fossil fuel f is produced according to a nested CES function combining a fuel-specific resource, R, and non-resource inputs (comprising capital, labor, and intermediate inputs), V:

$$(1) \qquad Y_f = \left[\alpha_f\, R_f^{\rho f} + (1-\alpha_f) V_f^{\rho f}\right]^{1/\rho f},$$

where Y, α, $\sigma_f = 1/(1-\rho_f)$ is output, the share coefficients of the CES function, and the elasticity of substitution between the resource and non-resource inputs, respectively. Given the form of the production function in equation (1), the elasticity of substitution between the resource and the rest of inputs in the top nest determines the price elasticity of supply (η_f) at the reference point according to[5]

$$(2) \qquad \eta_f = \sigma_f \frac{1-\alpha_f}{\alpha_f}.$$

Large-scale applied CGE models typically employ fuel supply elasticities for coal and natural gas ranging from, respectively, 0.8–1.2 and 0.5–0.8 (see, for example, the EPPA model, Paltsev et al. 2005; the GTAP model, Beckman, Hertel, and Tyner 2011; the USREP model, Rausch et al. 2010; and CIM-EARTH, Elliott et al. 2010). These supply elasticities imply elasticities of substitution for coal and natural gas of about 0.7 and 0.6, respectively.

Using the USREP model, we implement a carbon tax of $30 per metric ton of carbon dioxide ($t\mathrm{CO}_2$) in the West. Reflecting regional electricity markets, electricity is not traded between the West and other regions in our model, so our leakage calculations are not driven by changes in electricity trade. As for our stylized analysis, we simulate our policy scenario under two alternative model specifications: one with region-specific capital and labor (which does not allow for the ARE), and one with labor and capital that is perfectly mobile across regions (which does allow for the ARE). For each specification, we consider alternative values for σ^Y in the West and trade elasticities in all regions.[6]

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[4] This representation is similar to that used by Goulder, Hafstead, and Dworsky (2010).

[5] For the derivation of the relationship between η, α, and σ, see Rutherford (2002, p. 20).

[6] As noted in Section I, increasing σ^Y in the West allows us to consider abatement opportunities due to the availability of advanced technologies. An alternative approach is to explicitly model advanced technologies. To maintain

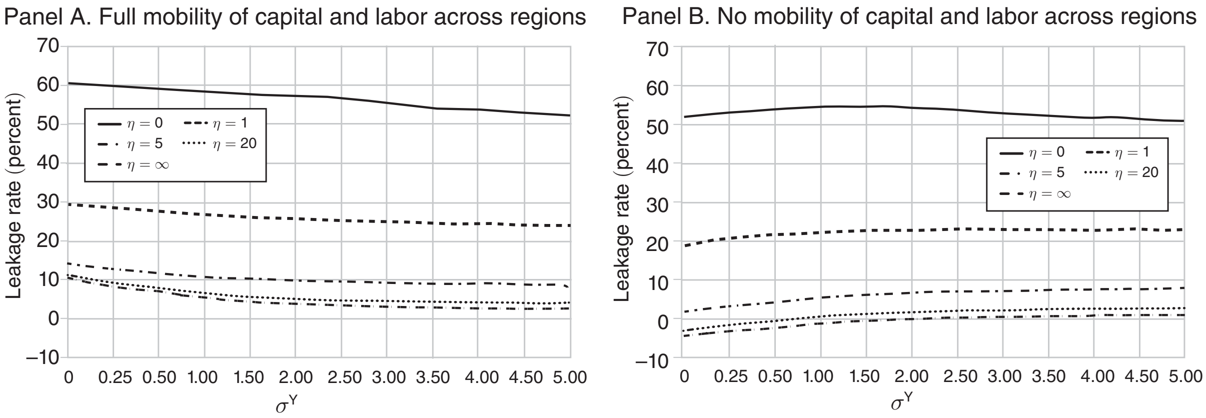

Figure 2. Leakage to Unconstrained US Regions

To be consistent with the empirical leakage literature, we report CO_2 leakage rates (the increase in emissions in unconstrained regions divided by the decrease in emissions in the West) in Figure 2. Similar to results from our stylized analysis, there is a strong positive relationship between leakage and the fossil fuel supply elasticity. Increasing σ^Y_{West} leads to a larger decrease in emissions in the West and greater displacement of fossil fuel to other regions, so the leakage rate may increase or decrease. Leakage is always positive for all elasticity combinations when capital and labor are fully mobile, both in the results presented in Figure 2 and results from a detailed sensitivity analysis.[7] We find that negative leakage occurs only if capital and labor are not mobile across regions, fossil fuel supply is close to perfectly elastic, and σ^Y is low. These results indicate that there is little potential for net negative leakage in calibrated general equilibrium models.

III. Conclusion

This paper investigated the potential for net negative leakage across regions in calibrated general equilibrium models. Analysis using a stylized model illustrated two important relationships. First, leakage is determined by the interaction of the elasticities of substitution in the production and utility functions, which influence the demand for carbon inputs, and the supply elasticity for the carbon inputs. Second, increasing the mobility of capital and labor may increase or decrease leakage.

Using a multiregion model of the United States, we found that allowing inter-regional mobility of capital and labor had little impact on leakage. Also, leakage was positive for virtually all parameterizations we considered. We conclude that there is little prospect for negative leakage in conventional numerical general equilibrium models. A key reason why leakage is positive is that numerical general equilibrium models are calibrated to fossil fuel supply elasticity values less than one, rather than the very high elasticity values required to generate net negative leakage in our analysis.

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consistency with the theoretical framework of FKB, we prefer to vary the value of σ^Y.

[7] In the online Appendix, we report results for "low" and "high" values for trade elasticities in all regions, where low and high values are equal to base values multiplied by, respectively, 0.5 and 2.

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