The Regional Greenhouse Gas Initiative: Emission Leakage and the Effectiveness of Interstate Border Adjustments

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Outline of Talk

1. Outline
2. Introduction
3. Theory
4. ICGE Modeling
5. Numerical Results
6. Summary
### The problem

- Multiple regions emitting greenhouse gases (GHGs) + limits on GHGs in a subset of jurisdictions ⇒ emissions from unconstrained regions increase, offsetting abatement
  - **Output-shifting/“pollution haven” effect**: abating regions import more GHG-intensive goods manufactured by unconstrained trade partners, who, in the face of increased demand for their products, expand production, emissions
  - **Input substitution/“rebound” effect**: contraction in abating regions’ energy demand depresses the traded price of fossil fuels in unconstrained jurisdictions, inducing substitution of FF’s for other inputs, increasing emission intensity of production

### Policy context

- Prior work focused exclusively at international level (Kyoto Protocol), where developed countries have binding GHG targets, developing countries don’t
- Recent developments in U.S. climate change policy mirror this “in-out” structure
  - California’s Global Warming Solutions Act (2006)
  - Regional Greenhouse Gas Initiative (RGGI)
Program highlights

- Supply-side cap-and-trade scheme to cut carbon dioxide (CO$_2$) emissions from electric power plants
- 10 New England + Mid-Atlantic states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York and Vermont)
- Pennsylvania, Washington DC + Canada’s Atlantic provinces participating as observers w/. no formal abatement commitments
- Objective: return generators’ CO$_2$ to 2002-2004 average emission levels by 2009-2014, reduce emissions by a further 10% in 2015-2019
- Emission control costs moderated by a “safety valve” provision (at $10/ton CO$_2$)
Issues and Research Questions

Issues

- Inter-regional electricity price differentials arbitrated by bulk power flows on a near real-time basis
- Higher electricity generating costs/power prices in RGGI states ⇒ electricity imports from unconstrained states ⇒ more coal-fired generation, CO₂ emissions
- Concern that utilities in RGGI states with outside generation assets will import power (Burtraw et al., 2006) ⇒ proposals for technical measures to neutralize leakage (Farnsworth et al., 2007)
- Implicit assumption: leakage confined to electric power sector!
- Focus mirrors use of partial equilibrium capacity expansion models (IPM, HAIKU) to analyze RGGI

Questions

- Need to understand how much leakage likely to occur, and why
- Precise amount of leakage debated (Farnsworth et al.: 18-25% of abatement in 2015 vs. American Council for an Energy-Efficient Economy: 60-90%)
- Our contribution: shrink range of estimates, characterize their dependence on key uncertain economic variables
- General equilibrium approach utilizing an interregional CGE (ICGE) model
A Simple Theoretical Model

Setup: the pollution haven effect

- Adapt Gerlagh-Kuik’s (2007) model w/. 2 regions: \( r \in \text{abaters} (A) \) non-abaters (N)
- Regions use CO\(_2\)-emitting fossil energy \((\varepsilon_r)\) to produce electricity \((q_r)\), latter traded
- Examine how
  - Reduction in \( \varepsilon_A \) + electricity imports \((t)\) ⇒ increase in \( \varepsilon_N \)
  - Countervailing tariff on electricity use \((\tau_A q_A)\) alleviates leakage
- Carbon-energy = non-traded good w/. region-specific prices \((\xi_r)\); electricity = perfectly homogeneous good w/. a single market-clearing price \((\pi)\)
- Identical upward-sloping isoelastic carbon-energy supply curves (elasticity \(\eta\)); downward-sloping isoelastic electricity demand curves (elasticity \(\delta\)).
- Identical generation technology: inputs of generic composite factor \((\zeta_r, \text{w/} \psi)\) + \(\varepsilon_r\) w/. cost share \(\alpha \in (0,1)\)
- Carbon-energy a necessary input ⇒ \(\sigma \in (0,1]\) = elasticity of substitution b/w. \(\varepsilon\) and \(\zeta\)
- Production and cost functions and energy demands:
  \[ q_r = F(\varepsilon_r, \zeta_r; \sigma), \quad \pi = G(\xi_r, \psi; \sigma) \quad \text{and} \quad \varepsilon_r = H(\xi_r, \pi, q_r; \sigma) \]
- Simplifying assumption 1: \(\psi\) unaffected by emission limit. Allows us to hold generic factor offstage, focus on CO\(_2\)!
Inter-regional power trade

- Electricity demand > supply in A, supply > demand in N ⇒ A generates power for domestic use, N exports t units of power to A
- Simplifying assumption 2: identical electricity demand in both regions ⇒ trade makes up the same share of consumption (β)
  \[ \frac{t}{q_A + t} = \frac{t}{q_N - t} = \beta \in (0, 1) \Rightarrow q_A = t(1 - \beta) / \beta \text{ and } q_N = t(1 + \beta) / \beta \]
- Simplifying assumption 3: initially identical thermodynamic efficiencies in generation
  \[ \frac{\epsilon_N}{\epsilon_A} = \frac{q_N}{q_A} = \frac{1 + \beta}{1 - \beta} > 1 \]
- A has cleaner production but dirtier consumption (characteristic of RGGI states)

Border adjustments

- A’s preferred instrument to neutralize leakage: tariff on foreign electricity
- BUT fundamental limitation of being unable to discriminate between domestically produced and imported power (intentionally discriminatory character of instrument violates commerce clause—Bolster, 2006; Farnsworth, 2007; Weiner, 2007)
- A imposes a tax \( \tau_A^q \) on all electricity consumed within its borders ⇒ producers + consumers see gross-of-ad-valorem-tariff price \((1 + \tau_A^q)\pi\)
Theoretical Model: Algebraic Summary

Model solved in terms of “hat algebra” (Fullerton-Metcalf, 2001)

Regional carbon-energy supplies:

\[
\hat{\epsilon}_A = \eta \hat{\xi}_A, \quad (1a)
\]

\[
\hat{\epsilon}_N = \eta \hat{\xi}_N, \quad (1b)
\]

Regional electricity demands:

\[
(1 - \beta)\hat{q}_A + \beta \hat{t} = -\delta (\hat{\pi} + \hat{\tau}^q_A), \quad (2a)
\]

\[
(1 + \beta)\hat{q}_N - \beta \hat{t} = -\delta \hat{\pi}. \quad (2b)
\]

Cost function incorporating A’s electricity tax:

\[
\hat{\pi} + \hat{\tau}^q_A = \alpha \hat{\xi}_A, \quad (3a)
\]

\[
\hat{\pi} = \alpha \hat{\xi}_N. \quad (3b)
\]

Regional carbon-energy demands:

\[
\hat{\epsilon}_A = \hat{q}_A + \sigma (\hat{\pi} + \hat{\tau}^q_A - \hat{\xi}_A), \quad (4a)
\]

\[
\hat{\epsilon}_N = \hat{q}_N + \sigma (\hat{\pi} - \hat{\xi}_N). \quad (4b)
\]

We treat \(\hat{\epsilon}_A < 0\) as a policy variable, drop (1a), solve remaining 7 eqs. in as many unknowns. Also examine effects of tax alone, solving full model for unknowns as f’ns of parameters, \(\hat{\tau}^q_A\).
Theoretical Model: Key Results

- Emission limit ↓ A's generation, tariff has opposite effect ⇒ overall sign ambiguous
  \[
  \hat{q}_A, \hat{\xi}_A \downarrow \text{ in } -\hat{\varepsilon}_A, \uparrow \text{ in } \hat{\tau}^q_A
  \]
- Effects on N’s electricity exports, generation, emissions and energy price qualitatively similar to one another, but opposite in sign to above:
  \[
  \hat{\pi}, \hat{\tau}, \hat{q}_N, \hat{\xi}_N \uparrow \text{ in } -\hat{\varepsilon}_A, \downarrow \text{ in } \hat{\tau}^q_A
  \]
- Leakage is inevitable unless emission cap accompanied by restraint on electricity trade:
  \[
  \Lambda = -\frac{d\varepsilon_N}{d\varepsilon_A} \propto 1 + \frac{[\alpha\delta + \sigma(1-\alpha)(1-\beta)]\hat{\tau}^q_A}{\alpha(1-\beta)\hat{\varepsilon}_A} < 1
  \]
  \[
  \hat{\tau}^q_A = 0 \Rightarrow \Lambda > 0, \text{ independent of } \hat{\varepsilon}_A, \uparrow \text{ in } A's \text{ import share of electricity consumption, elasticity of } N's \text{ carbon-energy supply; } \downarrow \text{ in the price elasticity of electricity demand, carbon-energy cost share in generation}
  \]
- Leakage can never cause overall emissions (\(E\)) to ↑ above baseline levels (cf. Babiker, 2005)
- Tariff limits leakage by stimulating import substitution via an increase in A's domestic electricity supply, while simultaneously attenuating demand.
- \(\Lambda\) decreasing in \(\hat{\tau}^q_A\), which neutralizes leakage if
  \[
  \hat{\tau}^q_{A,0} = -\frac{\alpha(1-\beta)}{\alpha\delta + \sigma(1-\alpha)(1-\beta)} \hat{\varepsilon}_A > 0
  \]
- Zero-leakage tariff increasing in electricity demand elasticity; decreasing in A’s electricity import intensity, generators’ carbon-energy cost share, substitution elasticity
- For any \(\hat{\varepsilon}_A\), sufficiently high electricity tariff can reverse leakage by limiting demand for N’s exports to the point where its generation falls, inducing \textit{de facto} abatement
Theoretical model: Insights from Numerical Parameterization

### Numerical Results ($\alpha = 0.3, \beta = 0.03, \delta = 0.5, \eta = 1, \sigma = 0.8$)

<table>
<thead>
<tr>
<th></th>
<th>RGGI Only</th>
<th>RGGI With Border Measures</th>
<th>Border Measures Only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(\tau^q_A = 0)$</td>
<td>$(\tau^q_A = \tau^q_{A,0})$</td>
<td>$(\tau^q_A = \tau^q_{A,0})$</td>
</tr>
<tr>
<td>1. Carbon-energy price</td>
<td>$\hat{\xi}_A$</td>
<td>0.030</td>
<td>0.107</td>
</tr>
<tr>
<td></td>
<td>$\hat{\xi}_N$</td>
<td>0.030</td>
<td>-</td>
</tr>
<tr>
<td>2. Electricity output</td>
<td>$\hat{q}_A$</td>
<td>-0.059</td>
<td>-0.017</td>
</tr>
<tr>
<td></td>
<td>$\hat{q}_N$</td>
<td>0.047</td>
<td>-</td>
</tr>
<tr>
<td>3. Electricity price</td>
<td>$\hat{\pi}$</td>
<td>0.009</td>
<td>-</td>
</tr>
<tr>
<td>4. Electricity trade</td>
<td>$\hat{\tau}$</td>
<td>1.768</td>
<td>-</td>
</tr>
<tr>
<td>5. Carbon-energy demand</td>
<td>$\hat{\varepsilon}_A - \hat{q}_A$</td>
<td>-0.076&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.076&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>$\hat{\varepsilon}_N$</td>
<td>0.030</td>
<td>-</td>
</tr>
<tr>
<td>6. Emission intensity</td>
<td>$\hat{\varepsilon}_A - \hat{q}_A$</td>
<td>-0.017</td>
<td>-0.060</td>
</tr>
<tr>
<td></td>
<td>$\hat{\varepsilon}_N - \hat{q}_N$</td>
<td>-0.017</td>
<td>-</td>
</tr>
<tr>
<td>7. Leakage</td>
<td>$\Lambda$</td>
<td>0.420</td>
<td>-</td>
</tr>
<tr>
<td>8. No-leakage tax</td>
<td>$\hat{\tau}^q_{A,0}$</td>
<td>0.032</td>
<td>0.032&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Exogenously imposed values.
A simple ICGE model (updated version of Sue Wing, 2007)

Model structure

- In contrast to prior sub-national CGE studies (Partridge-Rickman 1998), present model resolves 50 states + DC simultaneously
- 10 industry sectors: bi-level CES prod’n f’n of fuel and non-fuel intermediate inputs, value-added; imperfect interstate labor + capital mobility
- Simplified interstate trade using Armington structure: each good has single aggregate consumer price = CES aggregate of state-level producer prices
- Simplified tax structure: representative state agents, no gov’t, lump-rum revenue recycling to hholds in state where tax levied

Industries

<table>
<thead>
<tr>
<th>A. Fossil Fuels</th>
<th>C. Non-Energy Goods/Sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Petroleum</td>
<td>+ Chemicals + Metals + Pulp &amp; Paper)</td>
</tr>
<tr>
<td>4. Electric power</td>
<td>9. Transportation</td>
</tr>
<tr>
<td>5. Crude oil &amp; gas</td>
<td>10. Rest of the economy (Agriculture + Mining</td>
</tr>
<tr>
<td></td>
<td>+ Construction + Services + Government)</td>
</tr>
</tbody>
</table>
Representation of Production and Imperfect Factor Mobility in the Model

\[ y_{j,s} = \sigma_Y = 0 \]

Intermediate Materials \[ \sigma^M = 0 \] Energy \[ \sigma^E = 0.7 \] Value-Added \[ \sigma^{VA} = 1 \]

\[ x_{m,j,s} \quad k_{j,s} \quad l_{j,s} \]

\( \sigma^M \) = Elasticity of substitution among intermediate material inputs \( (x_{m,j,s}) \); \( \sigma^E \) = Elasticity of substitution among intermediate energy inputs \( (x_{e,j,s}) \); \( \sigma^{VA} \) = Elasticity of substitution between labor \( (l_{j,s}) \) and capital \( (k_{j,s}) \); \( \sigma^Y \) = Elasticity of substitution among energy, materials and value-added.

(a) Industries’ nested production functions

\[ A^L = \text{aggregate labor supply in destination state } d; \sigma^{LA} = \text{Elasticity of substitution among labor endowments of origin states } o \ (K_o); \sigma^{LT} = \text{Elasticity of transformation between aggregate and sector-specific labor at } d \ (l_{j,d}); A^K = \text{aggregate capital supply}; \sigma^{KA} = \text{Elasticity of substitution among origin states’ capital endowments } (K_o); \sigma^{KT} = \text{Elasticity of transformation between aggregate and sector-specific capital } (k_{j,d}) \]

(b) Imperfect interstate and intersectoral factor mobility

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RGGI, Emission Leakage and Interstate Border Adjustments
BLS social accounting matrix (SAM) for 2004, adjustments to intermediate energy demand using EIA data

SAM regionalized using BEA data: column disaggregation of value-added using state GDP components, commodity × state disaggregation of total final use using ASPI

Column disaggregation of non-energy intermediates: value shares of goods in given sector the same for all states = share in aggregate SAM

Intermediate + final demands for energy imputed from EIA state energy data

Factor supply acc’t: derive value of states labor endowments using agg. demand from GSP, 2000 census county-to-county worker flow files, capital remuneration computed as residual ASPI

Caveats: no interstate trade matrices (creating need for Armington assumption), no data on components of final demand ⇒ only crude estimates of terms-of-trade effects, welfare calculations based on income not consumption
Model Calibration and Policy Experiments

Calibration

- Model formulation as MCP, benchmark numerical calibration + replication w/. MPSGE
- Simulate year 2015 as target date for proposals to regulate CO₂
- Scale benchmark state factor endowments at historical state GDP growth rates
- Estimate elasticity of energy intensity w.r.t. state GDP (cf. Metcalf, 2007), compute energy-intensity decline factors, scale energy coeffs. in cost, expenditure f’ns
  \[
  \log \left( \frac{E}{Y} \right)_s = 0.0001 + 0.605 \log \left( \frac{E}{Y} \right)_{s,-1} - 0.240 \log Y_s - 0.066 \log P_s^E + 0.109 \log HDD_s.
  \]
  (0.0004) (0.016) (0.013) (0.005) (0.011)

  LR E/Y income elasticity \( \Omega = \frac{\omega_2}{1 - \omega_1} = -0.61 \), S.E. 0.05

Policy experiments

- Intra-state allowance trading under individual RGGI emission targets (autarkic state abatement)
- Inter-state allowance trading under aggregate RGGI cap
- Harmonized tariffs on electricity consumption in RGGI states: search over values to find leakage-neutralizing tax
Average Annual Growth Rates of State GDP and Energy Intensity, 2005-2015

Projection of average annual growth rates of state GDP and energy intensity from 2005 to 2015. The graph shows the projected growth rates for different states, with lines indicating the expected growth rate and its standard deviation. The graph also highlights the participating states in the RGGI program.
Overview of Results and Sensitivity Cases

**Base Case Results**

- Allowance price: $2.70 / ton CO$_2$
- Increase in elec. imports: 3.3%
- **Leakage rate: 49%**
- Aggregate U.S. net abatement: 3.3 MTCO$_2$
- Leakage-neutralizing electricity tax: 2.5%
- RGGI abatement after elec. tax imposed: 6.7 MTCO$_2$
- RGGI-wide change in per capita ASPI (with recycled tax revenues): +$5

**Sensitivity Cases**

- Income elasticity of E/GDP ±2 S.D.
- Autonomous energy efficiency improvement (AEEI) at 1% and 0.5% per annum
- GDP growth rate ± 1 SD
- $2/0.5 \times$ interfuel substitution elasticity
- $2/0.5 \times$ Armington elasticity of substitution for electricity
- $2/0.5 \times$ Armington elasticity of substitution for coal, oil, gas
BAU Scenario: Interstate Electricity Market Disposition

The diagram shows the BAU scenario for interstate electricity market disposition. It includes production, consumption, and net trade data for various states. The states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and RGGI.

- **Production** is represented by blue bars.
- **Consumption** is represented by red bars.
- **Net Trade** is represented by yellow bars.

The net trade values indicate the balance between production and consumption for each state, showing whether there is a surplus or deficit of electricity trade.
BAU Scenario: Importance of Electric Power for CO₂ Emissions

- BAU Scenario: Importance of Electric Power for CO₂ Emissions
- 22% of aggregate U.S. CO2 emissions
- 8% of U.S. electric sector CO2 emissions

Graph: MTCO₂
- Connecticut
- Delaware
- Maine
- Maryland
- Massachusetts
- New Hampshire
- New Jersey
- New York
- Rhode Island
- Vermont
- RGGI

Legend:
- 2015 Emissions (Left Scale)
- Power Sector Share (Right Scale)

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RGGI, Emission Leakage and Interstate Border Adjustments
RGGI Interstate Emission Trading: “Hot Air”

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RGGI, Emission Leakage and Interstate Border Adjustments
Sensitivity: Impacts on Allowance Prices, Electricity Trade and Leakage

Unlikely to be seen in practice as would trigger RGGI safety valve provision.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Impact on Allowance Prices</th>
<th>Impact on Electricity Trade</th>
<th>Impact on Leakage Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>2004 $/ton CO₂</td>
<td>0.5% p.a. AEE</td>
<td>1% p.a. AEE</td>
</tr>
<tr>
<td>$Ω = -0.51 (+2 S.D.)$</td>
<td>$Ω = -0.71 (-2 S.D.)$</td>
<td>$GDP growth rates +1 S.D.$</td>
<td>$GDP growth rates -1 S.D.$</td>
</tr>
<tr>
<td>1% p.a.</td>
<td>0.5% p.a.</td>
<td>AEE</td>
<td>AEE</td>
</tr>
<tr>
<td>0.5 x</td>
<td>0.5 x</td>
<td>AEE</td>
<td>AEE</td>
</tr>
<tr>
<td>0.5 x</td>
<td>0.5 x</td>
<td>AEE</td>
<td>AEE</td>
</tr>
<tr>
<td>2 x</td>
<td>2 x</td>
<td>AEE</td>
<td>AEE</td>
</tr>
<tr>
<td>0.5 x</td>
<td>0.5 x</td>
<td>AEE</td>
<td>AEE</td>
</tr>
</tbody>
</table>
Sensitivity: Leakage Disposition and Importance of Non-Electric Sectors

- Base Case
- $\Omega = -0.51 (+2 \text{ S.D.})$
- $\Omega = -0.71 (-2 \text{ S.D.})$
- 1% p.a. AEE
- 0.5% p.a. AEE
- GDP growth rates $+1 \text{ S.D.}$
- GDP growth rates $-1 \text{ S.D.}$
- $d_E = 1.4 (2 \times)$
- $d_E = 0.35 (0.5 \times)$
- $e_A,\text{Ele.} = 8 (2 \times)$
- $2 \times e_A,\text{Ele.} = 2 (0.5 \times)$
- $0.5 \times e_A,\text{Ele.}$

MTCO₂

Internal
External Ele. Sector
External Non-Ele. Sector
Total

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RGGI, Emission Leakage and Interstate Border Adjustments
Sensitivity: Leakage-Neutralizing Electricity Tariffs

- Base Case
- $\Omega = -0.51$ (2 S.D.)
- $\Omega = -0.71$ (-2 S.D.)
- 1% p.a. AEEI
- 0.5% p.a. AEEI
- GDP growth rates +1 S.D.
- GDP growth rates -1 S.D.
- $dE = 1.4$ (2 x)
- $oE = 0.35$ (0.5 x)
- $oA,Ele. = 8$ (2 x)
- $2 \times oA,e\neq Ele.$
- $0.5 \times oA,e\neq Ele.$

%
Sensitivity: Leakage Disposition in the Presence of Electricity Tariffs

<table>
<thead>
<tr>
<th>Scenario</th>
<th>MTCO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td></td>
</tr>
<tr>
<td>Ω = 0.51 (+2 S.D.)</td>
<td></td>
</tr>
<tr>
<td>Ω = 0.71 (-2 S.D.)</td>
<td></td>
</tr>
<tr>
<td>1% p.a. AEEI</td>
<td></td>
</tr>
<tr>
<td>0.5% p.a. AEEI</td>
<td></td>
</tr>
<tr>
<td>GDP growth rates +1 S.D.</td>
<td></td>
</tr>
<tr>
<td>GDP growth rates -1 S.D.</td>
<td></td>
</tr>
<tr>
<td>σE = 1.4 (2 ×)</td>
<td></td>
</tr>
<tr>
<td>σE = 0.35 (0.5 ×)</td>
<td></td>
</tr>
<tr>
<td>σA,Ele. = 8 (2 ×)</td>
<td></td>
</tr>
<tr>
<td>σA,Ele. = 2 (0.5 ×)</td>
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</tr>
<tr>
<td>2 × σA,e≠Ele.</td>
<td></td>
</tr>
<tr>
<td>0.5 × σA,e≠Ele.</td>
<td></td>
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</tbody>
</table>

Legend:
- Internal
- External Ele. Sector
- External Non-Ele. Sector
- Total

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RGGI, Emission Leakage and Interstate Border Adjustments
Conclusions

RGGI caps bind lightly on participating states’ economies

- Substantial “hot air” introduced by non-binding targets in New York, Maryland
- Allowance prices typically in $2-7 range, only exceed $10 safety valve threshold if state energy intensities decline much more slowly than historically
- Small primary abatement burden + recycled permit revenues = slight increases in per capita income
- Total net abatement of RGGI is small: < 4 MT in base case

Substantial induced CO₂ leakage

- Modest inflows of electric power to RGGI states
- Leakage rates fairly tightly clustered in 47-57% range
- Non-electric sectors in unconstrained states responsible for 1/3 of the problem

Countervailing electricity taxes

- Tax rate on electricity use in RGGI states of 2.5% neutralizes leakage in base case
- Taxes strongly attenuate RGGI states’ demand for imported power
- Induce substantial internal leakage, but w/ a smaller offsetting effect on primary abatement
The import substitution response induced by unilateral electricity taxes is effective in attenuating power inflows and leakage. Consequent increases in electricity prices are associated with an inward shift in the economy-wide demand curve for electricity. Result: smaller generation response outside RGGI, substitution of electricity for fossil fuels, and lower emissions there.