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

Ian Sue Wing and Marek Kolodziej

2008

RPP-2008-03

Regulatory Policy Program

Mossavar-Rahmani Center for Business and Government
John F. Kennedy School of Government
79 John F. Kennedy Street, Weil Hall
Cambridge, MA 02138

CITATION

This paper may be cited as: Sue Wing, Ian and Marek Kolodziej. 2008. “The Regional Greenhouse Gas Initiative: Emission Leakage and the Effectiveness of Interstate Border Adjustments,” Regulatory Policy Program Working Paper RPP-2008-03. Cambridge, MA: Mossavar-Rahmani Center for Business and Government, John F. Kennedy School of Government, Harvard University. Comments may be directed to the authors.

REGULATORY POLICY PROGRAM

The Regulatory Policy Program at the Mossavar-Rahmani Center for Business and Government provides an environment in which to develop and test leading ideas on regulation and regulatory institutions. RPP’s research aims to improve the global society and economy by understanding the impacts of regulation and creating better decisions about the design and implementation of regulatory strategies around the world. RPP’s efforts are organized around the following three core areas: regulation, markets, and deregulation; regulatory instruments; and regulatory institutions and policymaking.

FOR FURTHER INFORMATION

Further information on the Regulatory Policy Program can be obtained from the Program's director, Jennifer Nash, Mossavar-Rahmani Center for Business and Government, John F. Kennedy School of Government, 79 JKF Street, Cambridge, MA 02138, telephone (617) 384-7325, telefax (617) 496-0063, email jennifer_nash@harvard.edu.

The homepage for the Regulatory Policy Program can be found at: http://www.ksg.harvard.edu/m-rcbg/rpp/index.html

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

Ian Sue Wing[*] Marek Kolodziej

Dept. of Geography & Environment, Boston University

Abstract

We use theoretical and numerical general equilibrium models to analyze the Regional Greenhouse Gas Emission Initiative (RGGI), a cap-and-trade scheme to limit carbon dioxide emissions from electricity generators across ten states in the northeast U.S. Although RGGI's economic impacts are small, they induce substantial increases in power exports from unconstrained states which result in emission leakage rates of more than 50%. Harmonized taxes of 2-7% on electricity sales in participating states can neutralize leakage and increase aggregate abatement without significant adverse income effects. These results suggest that setting electricity tariffs in conjunction with the emission cap might improve RGGI's environmental performance.

Keywords: Computable general equilibrium models, Tradable permits, Regional climate change policy, Interstate electricity trade

JEL Codes: C68, F18, Q41, Q54, R13

---

[*] Corresponding author. Rm. 461, 675 Commonwealth Ave., Boston, MA 02215. Email: isw@bu.edu Ph.: (617) 353-5741. Fax: (617) 353-8399. This research was supported by U.S. Dept. of Energy Office of Science (BER) grant no. DE-FG02-06ER64204.

1 Introduction

In the context of climate change mitigation, the phenomenon of emission "leakage" arises where there are multiple sources of greenhouse gases (GHGs), and limits on the GHGs emitted by a subset of these entities causes emissions from uncontrolled sources to increase, wholly or partially offsetting the former's intended abatement.

Leakage arises as a consequence of trade among the jurisdictions in which sources reside. The key initiating factors in regions facing emission limits are the rising costs of producing energy- and emission-intensive goods, coupled with the falling demand for fossil-fuel precursors of GHGs. Each factor is associated with a different propagating mechanism:

- An output-shifting or "pollution haven" effect, whereby abating regions import larger quantities of relatively cheaper GHG-intensive goods manufactured by their unconstrained trade partners, who, in the face of increased demand for their products, expand production activity, energy use and emissions.[1]

- An input substitution or "rebound" effect, whereby the contraction in abating regions' energy demand depresses the traded price of fossil fuels and the relative price of energy in unconstrained jurisdictions, who substitute energy for other inputs to production, increasing the emission intensity of their manufactured goods.

Emissions thus appear to "leak out" from the constrained regions, offsetting the abatement there.

Investigations of leakage have been almost exclusively focused at the international level. The aim of this literature has been to characterize how global trade in fossil fuels and energy-intensive commodities interacts with the effects of the Kyoto Protocol, whose near-term targets cap rich nations' GHGs while allowing developing countries' emissions to continue

---

[1] Over the long run, firms' incentives to invest in plant and equipment where the inputs to production are relatively cheaper would also induce physical relocation of production capacity in energy-intensive industries to unconstrained regions.

essentially unabated.[2] However, U.S. domestic climate change policy has seen the emergence of a similar architecture of differentiated state-level GHG targets, with unilateral limits being adopted by California in 2020 and by ten New-England and Mid-Atlantic states in the electric power sector from 2009 onward. In this paper we focus on the latter policy, known as the Regional Greenhouse Gas Initiative (RGGI).

RGGI is a supply-side cap-and-trade scheme to reduce carbon dioxide (CO_2) emissions from electric power plants in Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York and Vermont,[3] with the goal of returning generators' CO_2 emissions to their average levels in 2002-2004 over the period 2009-2014, and abating emissions by a further 10% over the period 2015-2019. To moderate compliance costs, the policy also includes a "safety valve" provision, which allows generators to purchase allowances at \$10/ton CO_2 in the event that the traded price of permits rises above this level.[4]

In the context of this policy, leakage arises because inter-regional price differentials in electricity markets may be arbitraged by bulk power flows on a near real-time basis. Higher electricity generating costs and power prices in states participating in RGGI will therefore induce electricity imports from unconstrained states. In turn, the incentive facing unconstrained generators is to respond to this demand by generating additional electricity from low-cost GHG-intensive fuels such as coal, increasing their emissions of CO_2. Consequently, there is concern that electric utilities operating within the RGGI region who also own generation assets in neighboring states face strong financial incentives to avoid the emissions cap by importing power (Burtraw et al., 2006), which has led to a variety of proposals for addressing

---

[2] See, e.g., Felder and Rutherford (1993), Babiker (2001), Copeland and Taylor (2005), Babiker (2005), Babiker and Rutherford (2005).

[3] As of this writing Pennsylvania, Washington DC and Canada's Atlantic provinces are participating as observers in RGGI without undertaking formal emission reduction commitments.

[4] Jacoby and Ellerman (2004) provide an introduction to the safety valve, while Stavins (2006) discusses its application in the RGGI context. We will not say much more about this instrument because of the complicated nature of its provisions (e.g., rather than issue the necessary allowances, RGGI states will simply allow generators to purchase European Union Emission Trading Scheme or Clean Development Mechanism credits, which presumably will be available at lower cost), and the fact that its rules of operation have yet to be formally promulgated.

leakage through demand-side mandates.[5] The serious problem with all these measures is the implicit assumption that leakage will be confined to the electric power sector, which we shall see is unlikely to be fulfilled in practice.

Prerequisite to the analysis and selection of effective regulatory countermeasures is a thorough understanding of the magnitude of emission leakage, its origins within the economy, and the manner in which it is influenced by its precursors. The quantity of leakage is currently a matter of debate, with Burtraw et al. (2006) reporting a substantial rise in the revenues of non-RGGI generators due to increases in power exports to RGGI states under hypothetical scenarios for the year 2025, Farnsworth et al. (2007) concluding that leakage in 2015 is likely to be on the order of 18-25% of abatement, and the American Council for an Energy-Efficient Economy claiming leakage rates of 60-90%.[6] The contributions of this paper are to narrow the range of estimates, elucidate the strength of the forces that drive them, and characterize how these mechanisms depend on key uncertain parameters of the economy.

An important limitation of prior analyses of leakage is their reliance on partial equilibrium simulation models of the U.S. electricity sector, which do not adequately capture the interrelated effects of the household and interindustry demands for electricity and fossil fuels. To address this shortcoming we adopt the analytical approach employed by previous studies at the international level—computable general equilibrium (CGE) modeling. We use an updated version of the inter-regional CGE (ICGE) model introduced by Sue Wing (2007), which divides the U.S. economy into ten industries and the 50 states and the District of Columbia, and simulates the inter-industry and interstate interactions in the year 2015. The key feature of the model is its representation of trade in electricity, fossil fuels, and other goods and services through the use of an Armington scheme, which, following Babiker and Rutherford (2005), allows us to capture the effects of leakage-neutralizing border ad-

---

[5] These include further reducing electricity demand through end-use efficiency standards, mandating power purchases from low-carbon sources by load-serving entities (LSEs—i.e., power distributors), and a complementary demand-side allowance trading system which would cap the CO_2 associated with all electricity delivered by LSEs based on the growth of system load (Farnsworth et al., 2007).

[6] "The Magnificent Seven: States Take The Lead On Global Warming", Grapevine Online, Jan. 17, 2006 (`http://www.aceee.org/about/0601rggi.htm`).

justments using the simple device of harmonized tariffs on electricity consumption in RGGI states.

The quantity of leakage generated by RGGI and the effectiveness of border measures in countervailing these emissions fundamentally depend on the magnitude of abatement costs imposed by the RGGI cap. Table 1 presents the emission targets adopted by participating states, along with recent statistics on their electricity imports and power sector emissions (columns 1-3). Column 4 of the table presents a naive univariate time series projection of emissions in 2015. Comparison of these numbers with the CO_2 allowance allocations in column 5 reveals that the aggregate RGGI cap is only slightly lower than the projected emission baseline, which renders caps non-binding in many states, and leads to substantial excess allocation of allowances (so called "hot air"). The implication is that the aggregate RGGI cap binds only lightly on the economies of its participating states, a result which is borne out by our more sophisticated theoretical and numerical analyses.

We find that while the quantity of abatement induced by the RGGI emission target is small, its impact on electricity trade is large enough to generate leakage rates on the order of 50%. In our base-case scenario two thirds of these additional emissions emanate from the electric power sector in unconstrained states, while the remaining third is accounted for by *non*-electric sectors, in which firms and households substitute fossil fuels for electricity as the latter becomes relatively expensive. This effect manifests itself in unconstrained states ("external" leakage), and to a lesser extent within RGGI states as well ("internal" leakage). We show that modest border adjustments in the form of harmonized 2-7% tariffs on the electricity consumed in RGGI states are sufficient to entirely neutralize leakage. Despite questions about the constitutionality of such measures,[7] their efficacy indicates that RGGI's environmental objectives might be better served by taxing electricity use in conjunction with limits on generators' emissions.

The rest of the paper is organized as follows. In Section 2 we begin by illustrating the

---

[7] See Bolster (2006), Weiner (2007), Farnsworth et al. (2007).

phenomenon of leakage and conducting a preliminary numerical analysis using a simple theoretical model of the output-shifting effect. Section 3 describes the structure and calibration of the ICGE model, whose numerical results are presented and discussed in section 4. Section 5 offers policy implications and concluding remarks.

2 Some Simple Illustrative Theory

We begin with a simple theoretical elaboration of the leakage issue. Electricity is by nature a homogeneous commodity which can flow rapidly to among states to equalize interregional price differentials. By contrast, fossil fuels are much less geographically mobile, due both to the time and cost required to ship them and regulatory impediments to trade (e.g., air quality mandates for coal sulfur content or reformulated gasoline). For this reason, and to be able to characterize the influence of border measures, we focus on the output-shifting effect described in the introduction.

Inspired by the pollution haven model of Gerlagh and Kuik (2007), we partition the U.S. into two regions, one which decides to pursue emissions abatement (A) and another which does not (N), and identify these jurisdictions using the index $r = \{A, N\}$. Each region uses CO_2-emitting fossil energy (ε_r) to produce electricity (q_r), which is then traded. We use this framework to investigate how a mandated reduction in A's use of carbon-energy in the presence of electricity imports (t) results in leakage of emissions to N, and to examine how A's decision to impose a countervailing tariff on electricity (τ_A^q) may serve to alleviate leakage. In line with our focus on the market for electricity, we model carbon-energy as a non-traded good with region-specific prices (ξ_r), and model electricity as a perfectly homogeneous commodity with a single market-clearing price (π). We model the regions' carbon-energy supplies and electricity demands very simply, using identical upward-sloping isoelastic supply curves (with elasticity η), and downward-sloping isoelastic demand curves (with elasticity δ).

Both regions have the same electric power production technology, which uses inputs of ε_r and a generic composite factor ζ_r, whose price is ψ. Carbon-energy is a necessary input to electricity production, so the elasticity of substitution between ε and ζ is given by $\sigma \in (0, 1]$, and ε's cost share is given by $\alpha \in (0, 1)$. The production and cost functions and energy demands are then:

$$q_r = F(\varepsilon_r, \zeta_r; \sigma), \quad \pi = G(\xi_r, \psi; \sigma) \quad \text{and} \quad \varepsilon_r = H(\xi_r, \pi, q_r; \sigma).$$

To simplify the analysis we ignore general equilibrium influences on factor reallocation, and assume that the electricity sector makes up a sufficiently small share of the regions' output that ψ remains unaffected by the emission limit.

The centerpiece of our model is inter-regional trade in electric power. We assume a closed national electricity market in which demand exceeds supply in A and supply exceeds demand in N, with generators in A producing power solely for domestic use and generators in N exporting t units of power to satisfy A's demand. The quantities of electricity consumed in the regions are thus $q_A + t$ and $q_N - t$. To keep the algebra simple we assume that these two quantities are initially the same. Trade therefore makes up the same share of each region's consumption:

$$\frac{t}{q_A + t} = \frac{t}{q_N - t} = \beta \in (0, 1),$$

which enables us to express regional generation as $q_A = t(1-\beta)/\beta$ and $q_N = t(1+\beta)/\beta$. The additional assumption of initially identical thermodynamic efficiencies in electricity generation leads to the following useful expression for the baseline ratio of energy use and emissions:

$$\frac{\varepsilon_N}{\varepsilon_A} = \frac{q_N}{q_A} = \frac{1+\beta}{1-\beta} > 1.$$

The implication is that A has cleaner production but dirtier consumption, which is characteristic of RGGI signatory states as a group.

Border adjustments are the final element in the model. Our simple assumption is that the abating region attempts to neutralize leakage by implementing a tariff on foreign electricity, but faces the fundamental limitation of being unable to discriminate between domestically produced and imported power.[8] The upshot is that A imposes a tax τ_A^q on *all* electricity consumed within its borders, so that the price of electricity seen by producers and consumers alike is the gross-of-tariff price, which we specify in ad-valorem terms as $(1 + \tau_A^q)\pi$.

We formulate the model in log-differential form, using a "hat" over a variable to denote its logarithmic or fractional change—e.g., $\widehat{\pi} = d \log \pi = d\pi/\pi$ (Fullerton and Metcalf, 2002). A's gross-of-tax electricity price is approximated by $\widehat{\pi} + \widehat{\tau}_A^q$. The regional carbon-energy supply curves are given by

$$\widehat{\varepsilon}_A = \eta \widehat{\xi}_A, \tag{1a}$$

$$\widehat{\varepsilon}_N = \eta \widehat{\xi}_N, \tag{1b}$$

while the definition of β allows the regional electricity demands to be specified as:

$$(1 - \beta)\widehat{q}_A + \beta \widehat{t} = -\delta(\widehat{\pi} + \widehat{\tau}_A^q), \tag{2a}$$

$$(1 + \beta)\widehat{q}_N - \beta \widehat{t} = -\delta \widehat{\pi}. \tag{2b}$$

Logarithmically differentiating the cost function, setting $\widehat{\psi} = 0$, and incorporating A's tariff

---

[8] This assumption is admittedly simplistic. System operators and power marketers not only know the identity of the generating units bidding power onto the grid, they are able to infer their fuel mix as well. Thus, as a technical matter it is feasible to implement a tariff or a portfolio standard that would discriminate between constrained and unconstrained or high- and low-carbon generating units (Farnsworth et al., 2007). A key problem is that the intentionally discriminatory character of such instruments would likely violate the commerce clause of the U.S. constitution, and trigger legal challenges. For further discussion, see Bolster (2006), Farnsworth et al. (2007) and Weiner (2007).

on electricity, we have:

$$\widehat{\pi} + \widehat{\tau}_A^q = \alpha \widehat{\xi}_A, \tag{3a}$$

$$\widehat{\pi} = \alpha \widehat{\xi}_N. \tag{3b}$$

Assuming a constant elasticity of substitution (CES) form for the functions F, G and H allows us to close the model by expressing the differential regional demands for carbon-energy as follows:

$$\widehat{\varepsilon}_A = \widehat{q}_A + \sigma(\widehat{\pi} + \widehat{\tau}_A^q - \widehat{\xi}_A), \tag{4a}$$

$$\widehat{\varepsilon}_N = \widehat{q}_N + \sigma(\widehat{\pi} - \widehat{\xi}_N). \tag{4b}$$

Our theoretical model is made up of the eight linear equations (1)-(4) in the eight unknown variables $\widehat{\varepsilon}_A$, $\widehat{\xi}_A$, $\widehat{\varepsilon}_N$, $\widehat{\xi}_N$, $\widehat{q}_A$, $\widehat{q}_N$, $\widehat{\pi}$ and $\widehat{t}$. We represent the RGGI targets as a mandated reduction in A's use of carbon-energy, and designate $\widehat{\varepsilon}_A < 0$ as an exogenous policy variable. Doing this makes the system under-determined, so we drop the redundant carbon-energy supply function (1a) and solve the remaining equations for the seven unknowns in terms of the parameters α, β, δ, η, σ, the limit $\widehat{\varepsilon}_A$ and the tax $\widehat{\tau}_A^q$. The results elucidate the impacts of the electricity tax on leakage. To provide a clearer picture of the tariff's influence, we also examine the response of the economy to the tax alone without an emission limit. Our approach is to solve the full model for $\widehat{\varepsilon}_A$ along with the other unknowns as functions of the parameters and $\widehat{\tau}_A^q$.

Table 2(a) summarizes the solution to the model, which for every variable is linear in the emission limit and the tariff. The table gives the elasticities of each unknown with respect these parameters. The emission limit reduces A's domestic production of electricity, while the tariff has the opposite effect of stimulating generation, giving rise to an overall impact whose sign is ambiguous. In turn, the elasticities for N's electricity exports, generation, emissions and energy price all have the same signs, which are the opposite of those for $\widehat{q}_A$.

The results capture our description of the output-shifting effect, indicating that leakage arises through A's electricity imports, which expand to substitute for the shortfall in its domestic generation, and thereby induce a larger quantity of generation, energy use and emissions in N.

These results imply that leakage is inevitable unless the RGGI emission cap is accompanied by some type of restraint on electricity imports. The customary indicator of the strength of this effect is the leakage rate (Λ), given by the ratio of the increase in the non-abating region's emissions to the decrease in the abating region's emissions:

$$\Lambda = -\frac{d\varepsilon_N}{d\varepsilon_A} = -\frac{\varepsilon_N \widehat{\varepsilon}_N}{\varepsilon_A \widehat{\varepsilon}_A} \propto 1 + \underbrace{\frac{[\alpha\delta + \sigma(1-\alpha)(1-\beta)]\widehat{\tau}_A^q}{\alpha(1-\beta)\widehat{\varepsilon}_A}}_{(-)}. \tag{5}$$

Without the tariff, Λ is positive, constant, and independent of $\widehat{\varepsilon}_A$:

$$\Lambda|_{\widehat{\tau}_A^q=0} = \frac{\eta(1+\beta)}{\eta(1+\beta) + 2\left(\alpha\delta + (1-\alpha)\sigma\right)} < 1.$$

This result is a consequence of the linear relationship between $\widehat{\varepsilon}_N$ and $\widehat{\varepsilon}_A$, and indicates that leakage is increasing in A's initial share of electricity imports in consumption and the elasticity of N's fossil fuel supply, and decreasing in the price elasticity of electricity demand and the cost share of fossil fuels in power production. However, leakage can never cause overall emissions to increase above baseline levels, even in the absence of countervailing border adjustments. This outcome is apparent from the log-differential of aggregate emissions ($\mathcal{E} = \varepsilon_A + \varepsilon_N$), which, despite the fact that N's emissions may rise or fall, is unambiguously negative:[9]

$$\widehat{\mathcal{E}} = \underbrace{\tfrac{1}{2}(1-\beta)\widehat{\varepsilon}_A}_{(-)} + \underbrace{\tfrac{1}{2}(1+\beta)\widehat{\varepsilon}_N}_{(+/-)} < 0.$$

---

[9] Using a CGE simulation, Babiker (2005) finds that leakage rates can exceed 100 percent when there is trade in a perfectly homogeneous polluting good whose production exhibits increasing returns to scale. Our different conclusion rests on the key assumption of constant returns to scale in the CO_2-emitting industry.

Turning to the impact of border adjustments, the tariff limits leakage by stimulating import substitution via an increase in A's domestic electricity supply, while simultaneously attenuating demand. Table 2(a) is inconclusive as to whether the elasticities of the variables with respect to the limit are smaller than those with respect to the tariff, whether the results are more sensitive to the latter depends on the values of the parameters. Even so, Λ is decreasing in the tariff, which completely neutralizes leakage if

$$\widehat{\tau}^{q}_{A,0} = -\frac{\alpha(1-\beta)}{\alpha\delta + \sigma(1-\alpha)(1-\beta)}\widehat{\varepsilon}_A > 0. \tag{6}$$

For a given emission limit, the zero-leakage level of the tariff is increasing in the elasticity of electricity demand, and decreasing in both A's electricity import intensity as well as power generator's fossil fuel cost share and elasticity of substitution. The implication is that for any value of $\widehat{\varepsilon}_A$, a sufficiently high electricity tariff can reverse leakage by limiting demand for N's exports to the point where its production shrinks, inducing de facto reductions in emissions.

Lastly, we consider the effect of the cap on the emission intensity of generation, which falls in both regions in response to the emission limit.[10] The additional influence of the tariff is to amplify A's intensity decline by stimulating its generators to produce more electricity (implicitly, by substituting larger amounts of the clean generic factor for dirty carbon energy), and attenuate N's intensity decline by inhibiting the export supply response of its power sector.

To gain insight into RGGI's impacts we use develop preliminary numerical estimates based on the foregoing results. We parameterize the model by setting $\alpha = 0.3$ (NEA/IEA, 2005), $\beta = 3\%$ and $\widehat{\varepsilon} = -7.6\%$ (following the statistics in Table 1), and assuming elasticity values that are broadly consistent with the empirical literature: $\delta = 0.5$, $\eta = 1$ and $\sigma = 0.8$. Our findings, summarized in Table 2(b), indicate that RGGI's environmental impact is likely to be small. In the absence of border adjustments the price of carbon-energy in both regions

---

[10] A and N experience identical declines, which is an artifact of the model's simplifying assumptions.

rises by 3%, and the quantity of carbon-energy used by the unconstrained region rises by the same amount. A's electricity output declines by 5.9% while N's output rises by 4.7%, precipitating a neligible increase in power prices. Even so, electricity trade increases by more than one and a half times, resulting in a leakage rate of 42% and a decline in aggregate emissions of just over 2%. The zero-leakage electricity tariff implied by eq. (6) is small: 3.2%. Imposing this tax on A's electricity output generates a larger increase in the carbon-energy price (10.7%), a smaller decline in power output (1.7%) and a more than 50% increase in aggregate abatement.

Further insights can be obtained by looking at the consequences of imposing the no-leakage electricity tariff on A in the absence of an emission target. The analytical solution to the tax-only model is uninformative,[11] but applying the parameter values above yields the results in the last column of Table 2(b). Consistent with the elasticities in part (a) of the table, the tax pushes electric power production, and the price and quantity of carbon-energy inputs, upward in A and downward in N. Regions' emission intensities respond in the opposite manner due to the more elastic response of electricity output to the tax. The price of electricity declines slightly while trade is sharply curtailed, resulting in 100% leakage and unchanged overall emissions. This outcome suggests that, by itself, a tax on the emission-intensive good cannot reduce overall pollution because of the increased production stimulated by import substitution, and with it, demand for emission precursors. The key to the improvement in environmental performance is therefore the joint impact of the tariff's attenuation of production and emissions in the exporting region in conjunction with the emission limit's restraint on the additional pollution induced by import substitution.

We conclude this section by noting the caveats to our findings thus far. First, the prediction that RGGI's effect on the emission intensity of generation will be everywhere the same is an artifact of the two regions' identical market size and fuel mix. Relaxing these assumptions would certainly afford a more realistic characterization of RGGI's impact,

---

[11] The complete results are available from the authors upon request.

but at a cost of much greater algebraic complexity.[12] A second, related issue is that our analytical model is incomplete because it ignores the rebound effect. Taking account of this phenomenon would likely amplify the positive response of unconstrained states' emission intensities to abatement in RGGI states. Most importantly, the model's narrow focus on electric power also belies the fact that RGGI's influence on the relative price of electricity vis-à-vis fossil fuels will likely induce interfuel and energy-material substitution responses in other sectors of the economy, whose net impact cannot be precisely forecast. If the rise in electricity prices which attends the expansion of generation in unconstrained states results in substitution of material inputs for energy, then the leakage to non-electric sectors will likely be small. Conversely, leakage is likely to be large if the dominant response is substitution of CO_2-intensive fossil fuels for clean electricity.

Incorporating these factors into our analysis necessitates the use of a more detailed computational model, to which we now turn.

3 The ICGE Model

3.1 Model structure

We employ an updated version of the ICGE model introduced by Sue Wing (2007). The model is a static spatial price equilibrium simulation which divides the U.S. economy into 50 states and the District of Columbia (indexed by $s = \{1, \ldots, S\}$), and ten profit-maximizing industry sectors (indexed by $j = \{1, \ldots, N\}$). The model's sectoral disaggregation is shown in Table 3. Each sector produces a single homogeneous commodity, indexed by $i = \{1, \ldots, N\}$, and the set of commodities is partitioned into non-energy material goods (m) and energy goods (e), a subset of which is associated with emissions of CO_2.

In each industry and state, firms produce output ($y_{j,s}$) from capital ($k_{j,s}$), labor ($l_{j,s}$)

---

[12] Regionally distinguishing the trade weights ($\beta_A = t/(q_A + t) < \beta_N = t/(q_N - t) \in (0, 1)$) and carbon-energy shares ($\alpha_A < \alpha_N$) generates a complicated analytical solution which defies simple interpretation.

and an N-vector of intermediate inputs ($x_{i,j,s}$), according to the simple bi-level production function shown schematically in Figure 1(a). Each node of the tree represents the output of a sub-production function, the inputs to which are represented by the branches. Thus, output is a Leontief function of three inputs: a CES aggregate of energy intermediate goods, a CES aggregate of non-energy intermediate goods, and a Cobb-Douglas value-added composite of capital and labor. The dual of output is the producer price ($p_{j,s}$), defined as the unit cost of production gross of taxes on output.

Households in each state are modeled as a utility-maximizing representative agent with CES preferences over her consumption of commodities ($c_{i,s}$). Consumption is financed out of the income which each state agent receives from the rental of her endowments of labor (L_s) and capital (K_s) to industries. To proxy for the interactions between the price system and international trade in commodities, each state agent is endowed with a quantity of net exports of goods and services ($\overline{n}_{i,s}$), which for simplicity is kept fixed throughout the analysis.

Interstate trade is modeled very simply, using the Armington (1969) assumption. Aggregate supply of the i^{th} good (Y_i) is specified as an Armington CES composite of the 51 state varieties. Consequently, the demands for each commodity by industries and households in all states are fulfilled at a single, national market-clearing price (P_i) which is a weighted average of the s state-level producer prices. In terms of the leakage problem, a key limitation of this construct is its inability to represent the constraint of transmission capacity on bulk power flows. To capture the balance between this effect and the fluid character of electric power as a traded commodity, the base-case value of the Armington elasticity of substitution for electricity was set at 4. As we go on to show, large variations in this parameter had only a slight impact on the simulation results.

The model captures the imperfect mobility of factors across states and among industries through the use of transformation functions which are shown schematically in Figure 1(b). Imperfect factor mobility creates a divergence between each state's total demand for labor and capital and its corresponding endowments (L_s and K_s, respectively), so that $L_s \neq \sum_j l_{j,s}$

and $K_s \neq \sum_j k_{j,s}$. We assume that there is an economy-wide capital market in which all states supply capital at a common rental rate (R). Frictions in capital reallocation are modeled in a manner which is the opposite of that used for goods trade—by treating the demands for capital by industries in each state as a constant elasticity of transformation (CET) disaggregation of the economy-wide aggregate supply ($A^K = \sum_s K_s$). By contrast, labor markets are assumed to be geographically segmented, which causes wages to differ by state (W_s). Producers in each "destination" state (d) demand labor from surrounding "origin" jurisdictions (o) in addition to locally-supplied workers, a phenomenon which is captured using a composite CET-CES function. In each state, industries' demands for labor are a constant elasticity of transformation (CET) disaggregation of total labor demand ($A_d^L = \sum_j l_{j,d}$), which in turn is a CES composite of labor drawn from that state's own endowment as well as the endowments of its neighbors. The upshot is that within individual sectors, labor and capital are quasi-fixed inputs whose prices are differentiated by both industry and state ($w_{j,s}$ and $r_{j,s}$, respectively). Factor mobility is determined by the interstate and intersectoral differences in these prices, in conjunction with the elasticities of factor substitution and transformation shown in the diagram.

When emission limits are imposed in RGGI states, the resulting allowance prices ($\tau_s^{\mathrm{CO}_2}$) are synonymous with both implicit taxes on emissions and the marginal cost of abatement. The latter is expressed as a vector of commodity-specific markups on the prices of fossil fuels, the size of which is proportional to each fuel's carbon content, represented by emission factors ϕ_e.[13] Electricity generators then face a price of fossil fuels $P_e + \phi_e \tau_s^{\mathrm{CO}_2}$. Allowance prices exhibit complementary slackness with respect to the caps on states' electricity sector emissions (z_s), and in turn their use of fossil fuels. In the situation where each state complies

---

[13] The coefficients ϕ_e translate units of each fossil fuel into units of CO_2. To be consistent with aggregate economic and emissions data, they are calculated by dividing the benchmark quantity of total emissions associated with fuel e by the benchmark economic quantity of fuel demanded, $\sum_s \left(\sum_j \overline{x}_{e,j,s} + \overline{c}_{e,s} \right)$.

with its own target in autarkic fashion, we write this symbolically as

$$\varepsilon_s \leq z_s \quad \perp \quad \tau_s^{\mathrm{CO_2}}, \quad s \in \mathrm{RGGI},$$

where $\varepsilon_s = \sum_e \phi_e x_{e,\mathrm{Ele.},s}$ is the $\mathrm{CO_2}$ emitted in the course of the electric power sector's combustion of each type of fossil fuel. This expression represents intra-state emission trading, where generators in a particular state trade allowances only amongst themselves to equalize their marginal costs of $\mathrm{CO_2}$ control. To simulate interstate emission trading we solve the model for the common market-clearing price of permits across states ($\tau_s^{\mathrm{CO_2}} = \widetilde{\tau}^{\mathrm{CO_2}}$) which is consistent with the aggregate RGGI cap, $Z = \sum_{s \in \mathrm{RGGI}} z_s$:

$$\sum_{s \in \mathrm{RGGI}} \varepsilon_s \leq Z \quad \perp \quad \widetilde{\tau}^{\mathrm{CO_2}}.$$

Now, generators across RGGI states choose their levels of emissions optimally by setting their marginal cost of abatement equal to common market-clearing price of allowances, whose value is determined by the difference between Z and the business as usual (BAU) emission level.

The geographic pattern of welfare impacts depends on states' allowance allocations, z_s, given in Table 1. This may be seen by examining the definition of annual state personal income (ASPI) in the model:

$$\begin{aligned} \mathrm{ASPI}_s = {} & (W_s L_s + RK_s) + TR_s^{\mathrm{S}} + FE_s + NFA_s \quad \forall s \\ & + \begin{cases} \tau_s^{\mathrm{CO_2}} \varepsilon_s & \text{Intra-state Permit Trade} \\ \widetilde{\tau}^{\mathrm{CO_2}} (z_s - \varepsilon_s) & \text{Interstate Permit Trade} \end{cases} \quad s \in \mathrm{RGGI} \\ & + \tau^{\mathrm{Ele.}} P_{\mathrm{Ele.}} \left(c_{\mathrm{Ele.},s} + \sum_j x_{\mathrm{Ele.},j,s} \right) \quad s \in \mathrm{RGGI} \end{aligned} \tag{7}$$

Here, FE_s denotes federal government expenditures within each state, which indicate each state's receipts of recycled revenue from federal labor, capital and production taxes. The variable TR_s^{S} denotes recycled revenue from state labor, capital and production taxes, $NFA_s = \sum_i P_i \overline{n}_{i,s}$ indicates each state's net foreign asset position, and the term in parentheses is each state's factor income.[14]

The last two terms in eq. (7) represent the impacts of CO_2 allowance trading and recycled revenue from electricity tariffs. In the model, grandfathering of allowances to firms is equivalent to defining a new factor of production which is owned by households, the returns to which redound to each state representative agent. Auctioning allowances generates additional revenue to state governments which is then recycled to the corresponding representative agent. In both cases the simulated income effects are the same. With intra-state allowance trading the electric power sector is assumed to just comply with its emission target ($\varepsilon_s = z_s$). With interstate trading, if a state over-complies with its abatement target, or is allocated allowances in excess of its BAU level of emissions, its revenue rises due to permit sales. Conversely, a state which emits CO_2 in excess of its allocation will find it necessary to purchase allowances to stay in compliance, and will see its income decrease.

For transparency we represent border measures in the same way as our theoretical model. Our simple assumption is that RGGI states levy harmonized tariffs ($\tau^{\mathrm{ele.}}$) on electricity consumed within their borders, which allows us to boil the effects of more complicated schemes described in Farnsworth et al. (2007) down to a single metric—the RGGI-wide premium on the consumer price of electricity. Doing so allows us to search over values of this instrument to find the level of the tariff which just neutralizes the sum of internal and external leakage. An algebraic summary of the model is given in an appendix to the paper.

One final point bears mentioning. Because of the pre-existing distortionary taxes in the no-abatement equilibrium, the ultimate welfare impact in a given state depends on adverse effect of the primary burden of that jurisdiction's abatement on factor returns on one hand,

---

[14] The model is closed by imposing budgetary balance at the federal level $\sum_s FE_s = \sum_s TR_s^{\mathrm{F}}$ where TR_s^{F} is the revenue from the sum of federal taxes on labor, capital and production raised in each state. The basis for our closure rule is the assumption that the pattern of federal spending is invariant to climate policy, so that the ratio $\overline{\varpi}_s = FE_s / \sum_s FE_s$ remains the same, with or without RGGI. The value of $\overline{\varpi}_s$ is set equal to the state share of federal government spending in the benchmark dataset used to calibrate the model.

and benefits of recycled funds from pre-existing taxes, allowance allocations, and electricity tariffs on the other. We shall see that with policies such as RGGI which bind lightly on the economy, the first effect is sufficiently small that it is dominated by the second. The theory of the second best is the key to this result, as the general equilibrium effects of distorting production decisions in an initially tariff-ridden economy give rise to a net welfare *gain*.

3.2 Data, Parameters and Calibration

The model was calibrated on an inter-regional social accounting matrix (SAM) constructed from Bureau of Labor Statistics (BLS) nominal input-output data for the aggregate U.S. economy in 2004. Intermediate energy uses were adjusted using statistics from the Energy Information Administration's (EIA) Electric Power Annual. The resulting aggregate SAM was regionalized using Bureau of Economic Analysis (BEA) data on the components of state GDP and annual state personal income, as well as information on state energy consumption by fuel and sector from EIA's State Energy Data System. States' benchmark labor endowments were imputed using Journey to Work data from the 2000 Census, which allowed us to estimate benchmark capital earnings as residual value-added after taxes. We calibrated benchmark state and federal tax burdens by industry, as well as interstate revenue flows using data on state and federal tax revenues and expenditures from the Census Consolidated Federal Funds Report, Internal Revenue Service Databooks and supplemental state data files.[15] The final benchmark dataset is shown in Figure 2.

We construct our base-case projection of the economy in 2015 by scaling each state's benchmark endowments of labor and capital according to the historical average annual growth rates of state GDP, shown in Figure 3. To project BAU CO_2 emissions we eschew the customary use of a secular autonomous energy efficiency improvement (AEEI) factor to down-scale the coefficient on energy in the model's cost and expenditure functions ($\theta_{e,j,s}$ and $\alpha_{e,s}$).[16] Instead, we base our approach on Metcalf's (2007) recent finding that the growth of

---

[15] The procedures employed are described in detail by Sue Wing (2007).

[16] For discussion see, e.g., Sue Wing and Eckaus (2007).

states' incomes induces substantial declines in their energy-GDP ratios. We econometrically estimate the long-run income elasticity of energy intensity (Ω), which we use to compute state-specific average rates of energy intensity decline as a function of the growth of states' GDP. Our final step is to replace the AEEI index by compounding these declines into an energy-intensity scale factor, which we then use to down-scale $\theta_{e,j,s}$ and $\alpha_{e,s}$.

We proceed by estimating our own version of Metcalf's dynamic panel data model for the lower 48 states over the period 1970-2004 using EIA SEDS data on energy prices and energy consumption (P_s^E and E_s), BEA data on GDP, employment and imputed capital stocks (Y_s, L_s and K_s), and National Climatic Data Center series on heating and cooling degree days (HDD_s and CDD_s). Our preferred specification is:

$$\begin{aligned}\log\left(E/Y\right)_s = \omega_0 + \omega_1 \log\left(E/Y\right)_{s,-1} + \omega_2 \log Y_s + \omega_3 \log P_s^E \\ + \omega_4 \log HDD_s + \omega_5 \log CDD_s + \omega_6 \log\left(K/L\right)_s . \quad (8)\end{aligned}$$

We include state and time effects, as well as intercept and interaction dummies to control for idiosyncratic factors.[17] Estimating eq. (8) using the Arellano-Bond (1991) one-step procedure yields the following result:

$$\begin{aligned}\log(E/Y)_s = \underset{(0.0004)}{0.0001} + \underset{(0.016)}{0.605} \log\left(E/Y\right)_{s,-1} \\ \underset{(0.013)}{-0.240} \log Y_s \underset{(0.005)}{-0.066} \log P_s^E + \underset{(0.011)}{0.109} \log HDD_s.\end{aligned}$$

The long-run average income elasticity of energy intensity is given by $\Omega = \omega_2/(1-\omega_1) = -0.605$, with a standard error of 0.05. Applying this elasticity to the GDP growth rates

---

[17] We control for three factors: the influence of the transition in 1997 from SIC to NAICS industry groupings in the GDP and employment data, anomalous effects associated with the 1984 opening of a large synfuels facility in Beulah, SD, and the dramatic influx of low-sulfur coal from Powder River basin, WY, in the wake of railroad deregulation in the 1980s.

in Figure 3 yields the average annual rates of energy intensity decline shown on the same graph.

Table 4 summarizes the characteristics of the model's baseline solution in 2015. RGGI states account for a quarter of national income, and enjoy substantially higher per capita income than the rest of the U.S. Increases in energy efficiency are responsible for a 8-10% reduction in the relative price of electricity generation over the decade 2005-2015. The distribution of net interstate electricity trade across RGGI states parallels current conditions. Except for Delaware, RGGI states are projected to be net importers of electric power, whose inflows are concentrated in Connecticut, Maine, New York and New Jersey. Simulated BAU emissions are generally of the same magnitude as the econometric projections in Table 1.

4 Simulation Results

4.1 The Impacts of RGGI Under Base Case Parameter Assumptions

To elucidate the precursors of RGGI's impacts, we first conduct a simulation experiment in which only intra-state allowance trading is allowed. The results, which are summarized in panel A of Table 5, indicate that Maryland, New York and Vermont's allowance allocations exceed their BAU emissions, which results in a zero permit price and a slight inducement to increase generation in these states. Overall, RGGI states experience a modest decline in power production and an increase in the costs of generating electricity, with these impacts being concentrated in New Jersey, Maine and Rhode Island, where they are mirrored by the price of allowances. Interstate differences in the CO_2 intensity of generators' fuel mix mean that New Jersey, Massachusetts and Connecticut end up being responsible for the bulk of abatement. Electricity consumption is not materially affected, however, because RGGI states experience a 22% increase in imported power, with 42 and 59% increases in electricity imports by Rhode Island and Connecticut.

The RGGI caps reduce electric sector emissions by 17 $MTCO_2$, but half this amount is offset by increased emissions from outside RGGI—more than 8 MT from electric power and just under 3 MT from other industries.[18] As well, within RGGI, substitution of fossil fuels for electricity as the latter's price increases generates just under 1 MT of internal leakage. These results imply a net abatement of just under 5 $MTCO_2$, with an overall leakage rate of 71%.

Panel B summarizes the different set of impacts which arise when trade in allowances is permitted among generators in different states. Electricity consumption is virtually unchanged, and there is only a slight increase in the cost and attenuation in the quantity of electric power production. The expansion of electricity trade is also much smaller than occurs under autarkic state compliance, and is concentrated in Connecticut and New York. Allowance prices are in the \$2-3/ton range (in agreement with Farnsworth et al., 2007, p. 5) and abatement activity is less vigorous and more evenly distributed among the states. The reason is of course that Maryland, New York and Vermont sell their excess allowances, which then play the role of "hot air" in the trading system, relaxing the aggregate emission constraint by 10 MT. The consequent smaller increase in generation costs results in less leakage: 3.2 MT, relative to a base of 6.5 MT of gross electric sector CO_2 abatement. However, this still translates into a leakage rate of approximately 50%, which, although an improvement over intra-state allowance trading, comes at the cost of lower net abatement (3.3 MT).[19]

Not surprisingly, the level of the harmonized tariff required to neutralize leakage is quite low (2.5%), echoing the results of Section 2. As indicated in panel C, the tax imposes a slight additional adverse effect on electricity production, but has a neglibible additional impact

---

[18] The Armington trade structure does not permit us to pinpoint the origins of the additional electric power consumed by RGGI states, or the precise quantity of emissions associated therewith (i.e., separate from the confounding effects of general equilibrium adjustments in fuel markets). Nevertheless, in the simulation results Texas, Florida and Pennsylvania experience the largest expansion of electric generation.

[19] This figure represents 3.5% of baseline electric sector emissions (in excellent agreement with our theoretical model), but only 0.4% of the CO_2 emitted by RGGI states and 0.05% of aggregate U.S. emissions. Moreover, the ICGE model's Armington trade structure, general equilibrium interactions, and ability to account for the fact that RGGI states make up less than 15% of aggregate electricity consumption give rise to a modest increase in electricity trade (3.3%), a far cry from the more dramatic predictions of the theoretical model.

on electric sector abatement and allowance prices beyond the RGGI targets. Its impact on electricity consumption is far greater, but is still small in overall magnitude, reducing RGGI states' demand by about 1%. Even so, the tax has a effect substantial impact on bulk power flows, attenuating unconstrained states' electricity exports to RGGI by 25%, and reducing imports to Maryland and Massachusetts by more then one third. Interfuel substitution induced by the pass-through effect of the tariff on electricity prices precipates modest increases in the emissions of the non-electric sectors in RGGI states. However, in unconstrained states the effect is just the opposite: the inward shift of the economy-wide demand curve for electricity attenuates generators' supply responses, causing the traded price of power to decline and inducing firms and households to substitute electricity for fossil fuels. The resulting abatement (just over 3 MT) is sufficient to offset the additional internal leakage, and generates a net economy-wide emission reduction of 6.5 $MTCO_2$.

The pattern of changes in per capita income stimulated by these policies might appear counterintuitive at first glance. When there is only intra-state trade in allowances, those states with the highest marginal abatement costs see substantial *increases* in per-capita income, while the unconstrained states see slight declines. When we allow interstate trading all RGGI states see a small rise in income, an effect which is amplified by the imposition of the tariff on electricity.

Revenue recycling lies at the heart of this phenomenon, a point which is illustrated by Table 6's summary of the components of ASPI from eq. (7). The primary incidence of the costs of electric sector abatement and output tariffs falls on imperfectly mobile labor, and, to a lesser extent, capital, diminishing the returns to these factors. Recycled revenues from pre-existing state and federal factor and production taxes also decline slightly, while RGGI states' net foreign asset positions rise slightly as a result of improvements in their terms of trade.[20] However, the largest effect on the representative agents' budgets is the positive influence of recycled revenue from allowances and countervailing tariffs on electricity. As

---

[20] By raising electricity prices, emission constraints and the tariff increase the cost of producing electricity-intensive commodities.

alluded to above, this is a second-best result which arises because the RGGI emission targets bind lightly on their respective economies, which has a small distortionary impact that is easily mitigated by the additional income from recycled revenue. Similar gains in net income would likely not be experienced with more stringent targets that require substantial emission reductions and incur significant abatement costs.

4.2 Sensitivity Analysis

We now investigate the robustness of our findings to key uncertain economic processes represented by the model parameters. Specifically, we examine the influence of four factors: the assumed rates of state energy intensity decline, our projections of future economic growth based on recent trends in state GDP, and the assumed values for interfuel and interstate Armington energy elasticities of substitution. We proceed by perturbing each of the relevant parameters in a sequential fashion. The results are shown in Table 7. For each set of parameter changes we also run the model with the computed value of the leakage-neutralizing RGGI tariff, and summarize the results in Table 8.

Our base case (A) assumes default values for the income elasticity of energy intensity ($\Omega = -0.606$), the interfuel elasticity of substitution ($\sigma^E = 0.7$) and the Armington elasticities of substitution representing interstate trade in fossil fuels (σ^A_{Coal}, $\sigma^A_{\text{Crude Oil/Gas}}$, $\sigma^A_{\text{Gas}} = 0.8$; $\sigma^A_{\text{Petroleum}} = 1.4$) and electricity ($\sigma^A_{\text{Ele.}} = 4$). Case B tests the impact of uncertainty in the evolution of state energy intensity, first by varying Ω by ± 2 standard deviations relative to its mean (-0.71 and -0.51), and second by directly imposing slower growth rates for the energy-GDP ratio (1% and 0.5% p.a.) which understate historical trends but lie in the range of values of the AEEI parameter routinely employed by CGE models (Sue Wing and Eckaus, 2007). Case C examines the impact of our economic growth projections by varying the projected rates of growth of states' GDP in Figure 3 by ±1 standard deviation relative to their respective means. Cases D and E examine the influence of our choice of substitution elasticities, testing the substitutability among fuels in production and among geographic sources of electricity and fossil fuels (respectively) by doubling and halving σ^E and σ^A.

The impact of these parameters in order of increasing influence is as follows: Armington elasticities, interfuel substitution elasticities, economic growth and energy-intensity decline. The Armington elasticities of substitution have an negligibly small impact on the simulation results. The interfuel elasticity of substitution has a nonlinear effect—abatement and leakage rise when σ^E is doubled as well as when it is halved, with the latter effect being very slight.

In contrast with the predictions of our analytical model, when the rebound effect is accounted for, the aggregate emission intensity of electricity generation declines significantly within RGGI while rising slightly in unconstrained states. Except for the 0.5% and 1% AEEI cases where energy intensity declines more slowly than in the past—which would likely trigger RGGI's safety valve provision—aggregate electricity prices turn out to be largely unaffected by RGGI. Nonetheless, abating states increase their net imports of electric power, which, out of all the variables we examine, ends up being the most sensitive to variations in the parameters. The consequence for CO_2 abatement is that RGGI generators make modest emission reductions which are largely unaffected by internal leakage, slightly attenuated by the expansion of generation in unconstrained states, and substantially offset by interfuel substitution in non-electric industries outside the RGGI region. The result is that net aggregate emission reductions range from 0.5-24 MT, with corresponding leakage rates of 47-57%. Allowance prices are generally in the \$2-10 range, and recycled permit revenues, combined with the caps' small primary abatement burden, lead to slight increases in RGGI states' average per capita income.

Table 8 illustrates that the foregoing picture changes significantly once electricity taxes are imposed. The tariffs necessary to neutralize leakage are generally modest, in the range of 2-7% of the BAU electricity price. The combined costs of electricity taxes and emission abatement lead to higher power prices within RGGI states, which induce reductions in electricity demand and imports that are sufficiently large that the aggregate Armington electricity price experiences a slight decline, indicating an inward shift in the aggregate electricity demand curve. The emission intensity of RGGI generators remains the same, but that of power producers in unconstrained states now falls instead of expanding. Electric sector CO_2 abatement and allowance prices in RGGI are unaffected, but the overall cuts in emissions made by RGGI states are much smaller because their non-electric industries substitute away from more costly electricity toward now-cheaper toward fossil fuel inputs. The latter effect is more pronounced in RGGI states, but is offset by the dramatic reversal in the sign of leakage in the electricity sector in unconstrained states, where the attenuating effect of the tariff on exports of electricity to RGGI states induces generators to reduce their output, fossil fuel use, and emissions. Finally, the income effects of the cap-and-trade scheme and the tax and are twice as large those without the tax, as the tariff's beneficial revenue recycling effect outweighs its distortionary effect on factor returns. Notwithstanding this, the economic impact on RGGI states remains small.

5 Summary and concluding remarks

We have used a analytical and numerical models to analyze the economic and environmental impacts of the Regional Greenhouse Gas Initiative. Both of these effects are small due to the generous allocation of CO_2 emission allowances to electricity generators under RGGI's cap-and-trade system. The initiative's environmental effectiveness is further diminished by the ability of consumers within RGGI to import electricity from states not subject to emission limits, increasing the likelihood of larger inflows of bulk power and with them substantial leakage of emissions. Simulations indicate that 49-57% of the CO_2 abated by RGGI electric generators will be offset by unconstrained sources, with two-thirds of these emissions coming from the expansion of power production and export by generators in non-RGGI states, and the remainder from increases in the demand for fossil fuels by non-electric industries both outside and—to a lesser extent—inside of the RGGI umbrella.

More optimistically, we find that border measures—which we have modeled simply as harmonized tariffs on electricity consumed in RGGI states—can be an effective instrument to neutralize leakage when used in conjunction with a cap-and-trade system. Our numerical results show that taxes of 2-7% on electricity depress RGGI states' demand for power and cause an inward shift in the aggregate U.S. demand curve for electric power, which simultaneously attenuates the export response of generators in unconstrained states, reduces power prices, and induces household and industrial energy consumers to substitute electricity for fossil fuels. This last effect is dominant in unconstrained states, where its magnitude is large enough to offset the impact of the reverse (i.e., fossil fuel for electricity) substitution effect in RGGI's non-electric sectors as a result of higher power prices there. The upshot is that while cap on CO_2 induces RGGI states to export emissions to unconstrained counterparts, harmonized tariffs have the opposite effect of inducing exports of *abatement*, which can be thought of as "negative" or "reverse" leakage.

A key contribution of this paper has been to highlight the feedback mechanism whereby electricity taxes affect interfuel substitution in non-electric sectors, an effect which makes a sizable contribution to the overall quantity of emission leakage. But, as with any simulation study, our results are sensitive to the parameter values and structural assumptions of our numerical model. Our sensitivity analysis is an attempt to shed light on the implications of the former, but some aspects of the latter remain problematic, as we go on to elaborate.

Perhaps the most serious limitation of our ICGE model is the lack of data on state-to-state electric power flows and the consequent use of an Armington structure to model trade in electricity, which prevent us from simulating the effect of transmission constraints RGGI states' power imports. An attempt to capture the influence of these constraints by halving the benchmark value of the Armington elasticity of substitution had a negligible impact on the simulation results. However, given the admittedly heuristic character of this workaround, we prefer to interpret our finding as the upper bound on the true magnitude of leakage.

Lack of data on the components of income at the state level gives rise to a further shortcoming, namely, the inability of the model to distinguish between consumption and investment. Our characterization of RGGI's economic impacts is therefore restricted to near-term income effects, and resolves neither short-run consumption-based welfare impacts nor the influence of changes in investment on capital accumulation and long-run income growth.

A third issue involves the simple production function used to characterize producer behavior, which in the electric power sector glosses over the response of different generation technologies to the emission limit, particularly the inducement of renewables such as wind. While the ability to explicitly represent the expansion of low-cost electricity supply options within the model would likely lower our estimates of RGGI's costs, it should be noted that replacing a smooth production function with an array of discrete Leontief activities may have the opposite effect because of the diminished substitutability among inputs to the sector as a whole (Sue Wing, 2005). The implications for abatement costs and leakage therefore depend on the relative importance of these two influences.

Finally, we have entirely sidestepped the issue of volatility in RGGI states' baseline emissions, and its implications for whether the cap binds. Over the decade 1995-2004 CO_2 emitted by RGGI electric generators fluctuated markedly, so much so that the mean of the annual growth rates of emissions was less than one third of their standard deviation! To understand the sources of such volatility and their consequences for the expected magnitudes of RGGI's environmental and economic impacts, we would need to conduct a parametric uncertainty analysis, which is a separate undertaking that is beyond the scope of the present study.

The development of data and modeling techniques to address these issues is the focus of ongoing research by the authors.

Appendix: Algebraic Summary of the Model (Can be deleted in proof)

Prices

$p_{j,s}$	producer price index in industry j and state s
P_i	Armington commodity i price index, $i = \{e \text{ (energy)}, m \text{ (materials)}\}$
W_s	Wage in state s
$w_{j,s}$	Wage rate for sector-specific labor in industry j and state s
R	Aggregate capital rental rate
$r_{j,s}$	Rental rate of sector-specific capital in industry j and state s
P^U_s	Price of utility good in state s (= 1 in Washington DC, numeraire)

Activity levels

$y_{j,s}$	Output of industry j in state s
Y_i	Aggregate supply of Armington commodity i
A^L_s	Total labor demand in state s
A^K	Aggregate capital supply
U_s	Income level (utility) in state s

Parameters

$\theta_{e,j,s}$	Production coefficient on energy input e in industry j and state s
$\theta_{m,j,s}$	Production coefficient on material input m in industry j and state s
$\theta_{l,j,s}$	Production coefficient on labor in industry j and state s
$\theta_{k,j,s}$	Production coefficient on capital in industry j and state s
$\theta_{E,j,s}$	Production coefficient on energy aggregate in industry j and state s
$\theta_{M,j,s}$	Production coefficient on material aggregate in industry j and state s
$\theta_{VA,j,s}$	Production coefficient on value added in industry j and state s
$\mu_{j,s}$	State s share of Armington aggregate use in industry j
$\alpha_{i,s}$	Commodity i expenditure share of final use in state s

$\lambda_{o,s}$	Share of total labor demand in state s supplied by other states o
$\gamma_{j,s}$	Share of total labor supply in state s demanded by industry j
$\kappa_{j,s}$	Share of aggregate capital supply demanded by industry j in state s
$\overline{n}_{i,s}$	Net international exports of commodity i from state s
$\overline{\tau}^{L,t}_{j,s}$	Industry j/state s pre-existing labor taxes, $t \in \{\mathrm{S}\ (\text{state}), \mathrm{F}\ (\text{federal})\}$
$\overline{\tau}^{K,t}_{j,s}$	Industry j/state s pre-existing capital taxes, $t \in \{\mathrm{S}\ (\text{state}), \mathrm{F}\ (\text{federal})\}$
$\overline{\tau}^{Y,t}_{j,s}$	Industry j/state s pre-existing production taxes, $t \in \{\mathrm{S}\ (\text{state}), \mathrm{F}\ (\text{federal})\}$
$\tau^{\mathrm{CO}_2}_s$	CO_2 allowance price
ϕ_e	Energy commodity e stoichiometric CO_2 coefficient
ϖ_s	State s share of aggregate federal government spending in the base year

Elasticities of substitution and transformation

σ^E	Substitution among fuels	0.7
σ^{VA}	Capital-labor substitution	1.0
σ^A_j	Industry j interstate Armington substitution	0.8-4
σ^C	Substitution among final expenditure on commodities	0.5
σ^{KT}	Transformation between aggregate and sector-specific capital	0.25
σ^{LA}	Aggregation of labor across states	0.5
σ^{LT}	Transformation between state and sector-specific labor	0.5

Zero profit conditions

1. $N \times S$ conditions defining zero profit in the production of commodities within states,

complementary to the $N \times S$ activity levels of industries within states:

$$\begin{aligned}
p_{j,s} = {} & (1+\overline{\tau}^{Y,\mathrm{S}}_{j,s}+\overline{\tau}^{Y,\mathrm{F}}_{j,s}) \\
& \times \left[\frac{1}{\theta_{E,j,s}} \left\{ \sum_{e \neq \mathrm{Ele.}} \theta^{\sigma^E}_{e,j,s} (P_e + \phi_e \tau^{\mathrm{CO_2}})^{1-\sigma^E} + \theta^{\sigma^E}_{\mathrm{Ele.},j,s} (P_{\mathrm{Ele.}}(1+\tau^{\mathrm{Ele.}}))^{1-\sigma^E} \right\}^{1/(1-\sigma^E)} \right. \\
& \quad + \frac{1}{\theta_{VA,j,s}} \left\{ (1+\overline{\tau}^{L,\mathrm{S}}_{j,s}+\overline{\tau}^{L,\mathrm{F}}_{j,s}) w_{j,s} \right\}^{\theta_{L,j,s}} \left\{ (1+\overline{\tau}^{K,\mathrm{S}}_{j,s}+\overline{\tau}^{K,\mathrm{F}}_{j,s}) r_{j,s} \right\}^{\theta_{K,j,s}} \\
& \qquad \left. + \frac{1}{\theta_{M,j,s}} \sum_m P_m / \theta_{m,j,s} \right] \quad \perp \quad y_{j,s}, \quad j = \mathrm{Ele.}, s \in \mathrm{RGGI}
\end{aligned}$$

$$\begin{aligned}
p_{j,s} = {} & (1+\overline{\tau}^{Y,\mathrm{S}}_{j,s}+\overline{\tau}^{Y,\mathrm{F}}_{j,s}) \\
& \times \left[\frac{1}{\theta_{E,j,s}} \left\{ \sum_{e \neq \mathrm{Ele.}} \theta^{\sigma^E}_{e,j,s} P_e^{1-\sigma^E} + \theta^{\sigma^E}_{\mathrm{Ele.},j,s} (P_{\mathrm{Ele.}}(1+\tau^{\mathrm{Ele.}}))^{1-\sigma^E} \right\}^{1/(1-\sigma^E)} \right. \\
& \quad + \frac{1}{\theta_{VA,j,s}} \left\{ (1+\overline{\tau}^{L,\mathrm{S}}_{j,s}+\overline{\tau}^{L,\mathrm{F}}_{j,s}) w_{j,s} \right\}^{\theta_{L,j,s}} \left\{ (1+\overline{\tau}^{K,\mathrm{S}}_{j,s}+\overline{\tau}^{K,\mathrm{F}}_{j,s}) r_{j,s} \right\}^{\theta_{K,j,s}} \\
& \qquad \left. + \frac{1}{\theta_{M,j,s}} \sum_m P_m / \theta_{m,j,s} \right] \quad \perp \quad y_{j,s}, \quad j \neq \mathrm{Ele.}, s \in \mathrm{RGGI}
\end{aligned}$$

$$\begin{aligned}
p_{j,s} = {} & (1+\overline{\tau}^{Y,\mathrm{S}}_{j,s}+\overline{\tau}^{Y,\mathrm{F}}_{j,s}) \left[\frac{1}{\theta_{E,j,s}} \left\{ \sum_{e} \theta^{\sigma^E}_{e,j,s} P_e^{1-\sigma^E} \right\}^{1/(1-\sigma^E)} \right. \\
& \quad + \frac{1}{\theta_{VA,j,s}} \left\{ (1+\overline{\tau}^{L,\mathrm{S}}_{j,s}+\overline{\tau}^{L,\mathrm{F}}_{j,s}) w_{j,s} \right\}^{\theta_{L,j,s}} \left\{ (1+\overline{\tau}^{K,\mathrm{S}}_{j,s}+\overline{\tau}^{K,\mathrm{F}}_{j,s}) r_{j,s} \right\}^{\theta_{K,j,s}} \\
& \qquad \left. + \frac{1}{\theta_{M,j,s}} \sum_m P_m / \theta_{m,j,s} \right] \quad \perp \quad y_{j,s}, \quad s \notin \mathrm{RGGI} \qquad \text{(ZP1)}
\end{aligned}$$

2. N conditions defining zero profit in interstate trade in commodities, complementary to the N Armington aggregate commodity supply activity levels:

$$P_j = \left(\sum_s \mu^{\sigma^A_j}_{j,s} p^{1-\sigma^A_j}_{j,s} \right)^{1/(1-\sigma^A_j)} \quad \perp \quad Y_j \qquad \text{(ZP2)}$$

3. S conditions defining state-level expenditure on final uses, complementary to the S state income levels:

$$P_s^U = \left[\alpha_{\text{Ele.},s}^{\sigma^C}((1+\tau^{\text{Ele.}})P_{\text{Ele.}})^{1-\sigma^C} + \sum_{i\neq\text{Ele.}} \alpha_{i,s}^{\sigma^C} P_i^{1-\sigma^C}\right]^{1/(1-\sigma^C)} \quad \perp \quad U_s, \qquad s \in \text{RGGI}$$

$$P_s^U = \left[\sum_i \alpha_{i,s}^{\sigma^C} P_i^{1-\sigma^C}\right] \quad \perp \quad U_s, \qquad s \notin \text{RGGI} \tag{ZP3}$$

4. S conditions defining zero profit in the aggregation of states' labor and the transformation of the resulting supply into industry-specific labor, complementary to the S state-level labor supply activity levels:

$$\left(\sum_o \lambda_{o,s}^{\sigma^{LA}} W_o^{1-\sigma^{LA}}\right)^{1/(1-\sigma^{LA})} = \left(\sum_j \gamma_{j,s}^{\sigma^{LT}} w_{j,s}^{1-\sigma^{LT}}\right)^{1/(1-\sigma^{LT})} \quad \perp \quad A_s^L \tag{ZP4}$$

5. A single condition defining zero profit in the transformation of states' capital endowments into industry-specific capital, complementary to the activity level of aggregate capital supply:

$$R = \left(\sum_s \sum_j \kappa_{j,s}^{\sigma^{KT}} r_{j,s}^{1-\sigma^{KT}}\right)^{1/(1-\sigma^{KT})} \quad \perp \quad A^K \tag{ZP5}$$

Market clearance conditions

1. N conditions defining aggregate supply-demand balance for commodities, complemen-

tary to the N aggregate commodity prices:

$$\begin{aligned} Y_e = \sum_{s\in\text{RGGI}} \Bigg[& (1+\overline{\tau}^{\text{Y,S}}_{\text{Ele.},s}+\overline{\tau}^{\text{Y,F}}_{\text{Ele.},s})\frac{\theta^{\sigma^E}_{e,\text{Ele.},s}}{\theta_{E,\text{Ele.},s}}\left(\frac{p_{\text{Ele.},s}}{P_e+\phi_e\tau_s^{\text{CO}_2}}\right)^{\sigma^E} y_{\text{Ele.},s} \\ & + \sum_{j\neq\text{Ele.}}(1+\overline{\tau}^{\text{Y,S}}_{j,s}+\overline{\tau}^{\text{Y,F}}_{j,s})\frac{\theta^{\sigma^E}_{e,j,s}}{\theta_{E,j,s}}\left(\frac{p_{j,s}}{P_e}\right)^{\sigma^E} y_{j,s}\Bigg] \\ & + \sum_{s\notin\text{RGGI}}\sum_j(1+\overline{\tau}^{\text{Y,S}}_{j,s}+\overline{\tau}^{\text{Y,F}}_{j,s})\frac{\theta^{\sigma^E}_{e,j,s}}{\theta_{E,j,s}}\left(\frac{p_{j,s}}{P_e}\right)^{\sigma^E} y_{j,s} \\ & + \sum_s \alpha^{\sigma^C}_{e,s}\left(\frac{P^U_s}{P_e}\right)^{\sigma^C} U_s+\overline{n}_{e,s} \quad \perp \quad P_e, \quad e\neq \text{Ele.} \end{aligned}$$

$$\begin{aligned} Y_e = \sum_{s\in\text{RGGI}} \Bigg[& \sum_j\left\{(1+\overline{\tau}^{\text{Y,S}}_{j,s}+\overline{\tau}^{\text{Y,F}}_{j,s})\frac{\theta^{\sigma^E}_{e,j,s}}{\theta_{E,j,s}}\left(\frac{p_{j,s}}{P_e(1+\tau^{\text{Ele.}})}\right)^{\sigma^E} y_{j,s}\right\} \\ & + \alpha^{\sigma^C}_{e,s}\left(\frac{P^U_s}{P_e(1+\tau^{\text{Ele.}})}\right)^{\sigma^C} U_s+\overline{n}_{e,s}\Bigg] \\ + \sum_{s\notin\text{RGGI}}\Bigg[& \sum_j\left\{(1+\overline{\tau}^{\text{Y,S}}_{j,s}+\overline{\tau}^{\text{Y,F}}_{j,s})\frac{\theta^{\sigma^E}_{e,j,s}}{\theta_{E,j,s}}\left(\frac{p_{j,s}}{P_e}\right)^{\sigma^E} y_{j,s}\right\} \\ & + \alpha^{\sigma^C}_{e,s}\left(\frac{P^U_s}{P_e}\right)^{\sigma^C} U_s+\overline{n}_{e,s}\Bigg] \quad \perp \quad P_e, \quad e=\text{Ele.} \end{aligned} \tag{MC1a}$$

$$Y_m = \sum_s\left[\sum_j\frac{(1+\overline{\tau}^{\text{Y,S}}_{j,s}+\overline{\tau}^{\text{Y,F}}_{j,s})}{\theta_{m,j,s}\theta_{M,j,s}}y_{j,s}+\alpha^{\sigma^C}_{m,s}\left(\frac{P^U_s}{P_m}\right)^{\sigma^C}U_s+\overline{n}_{m,s}\right] \quad \perp \quad P_m \tag{MC1b}$$

2. $N\times S$ conditions defining supply-demand balance for industries' outputs, complementary to the $N\times S$ producer prices:

$$y_{j,s}=\mu^{\sigma^A_j}_{j,s}\left(\frac{P_j}{p_{j,s}}\right)^{\sigma^A_j}Y_j \quad \perp \quad p_{j,s} \tag{MC2}$$

3. S conditions defining aggregate supply-demand balance for labor across states, com-

plementary to the S average state wage levels:

$$L_s = \sum_d \lambda_{s,d}^{\sigma^{LA}} \left[\frac{\left(\sum_o \lambda_{o,d}^{\sigma^{LA}} W_o^{1-\sigma^{LA}} \right)^{1/(1-\sigma^{LA})}}{W_s} \right]^{\sigma^{LA}} A_d^L \quad \perp \quad W_s \tag{MC3}$$

4. $N \times S$ conditions defining the supply-demand balance for industry-specific labor within each state, complementary to the $N \times S$ industry-specific wage levels:

$$\begin{aligned} \gamma_{j,s}^{\sigma^{LT}} \left(\frac{W_s}{w_{j,s}} \right)^{\sigma^{LT}} A_s^L = (1 + \overline{\tau}_{j,s}^{Y,\mathrm{S}} + \overline{\tau}_{j,s}^{Y,\mathrm{F}}) \frac{\theta_{l,j,s}}{\theta_{VA,j,s}} \left\{ (1 + \overline{\tau}_{j,s}^{L,\mathrm{S}} + \overline{\tau}_{j,s}^{L,\mathrm{F}}) w_{j,s} \right\}^{\theta_{l,j,s}-1} & \\ \times \left\{ (1 + \overline{\tau}_{j,s}^{K,\mathrm{S}} + \overline{\tau}_{j,s}^{K,\mathrm{F}}) r_{j,s} \right\}^{\theta_{K,j,s}} \quad \perp \quad w_{j,s} & \quad \text{(MC4)} \end{aligned}$$

5. A single condition defining the supply-demand balance for aggregate capital, dual the aggregate rental rate:

$$\sum_s K_s = \sum_j \sum_s \kappa_{j,s}^{\sigma^{KT}} \left(\frac{R}{r_{j,s}} \right)^{\sigma^{KT}} A^K \quad \perp \quad R \tag{MC5}$$

6. $N \times S$ conditions defining the supply-demand balance for industry-specific capital, complementary to the $N \times S$ industry-specific rental rates:

$$\begin{aligned} \kappa_{j,s}^{\sigma^{KT}} \left(\frac{R}{r_{j,s}} \right)^{\sigma^{KT}} A^K = (1 + \overline{\tau}_{j,s}^{Y,\mathrm{S}} + \overline{\tau}_{j,s}^{Y,\mathrm{F}}) \frac{\theta_{k,j,s}}{\theta_{VA,j,s}} \left\{ (1 + \overline{\tau}_{j,s}^{L,\mathrm{S}} + \overline{\tau}_{j,s}^{L,\mathrm{F}}) w_{j,s} \right\}^{\theta_{l,j,s}} & \\ \times \left\{ (1 + \overline{\tau}_{j,s}^{K,\mathrm{S}} + \overline{\tau}_{j,s}^{K,\mathrm{F}}) r_{j,s} \right\}^{\theta_{K,j,s}-1} \quad \perp \quad r_{j,s} & \quad \text{(MC6)} \end{aligned}$$

Income balance conditions

S equations defining state income as the sum of factor returns and recycled tax revenue, complementary to the S prices of state "utility goods" (i.e., final consumption):

$$
\begin{aligned}
U_s = W_s L_s + R K_s + \sum_i P_i \overline{n}_{i,s} &+ \left(\sum_j \overline{\tau}^{L,\mathrm{S}}_{j,s} w_{j,s} l_{j,s} + \sum_j \overline{\tau}^{K,\mathrm{S}}_{j,s} r_{j,s} k_{j,s} + \sum_j \overline{\tau}^{Y,\mathrm{S}}_{j,s} p_{j,s} y_{j,s} \right) \\
&+ \varpi_s \sum_s \left(\sum_j \overline{\tau}^{L,\mathrm{F}}_{j,s} w_{j,s} l_{j,s} + \sum_j \overline{\tau}^{K,\mathrm{F}}_{j,s} r_{j,s} k_{j,s} + \sum_j \overline{\tau}^{Y,\mathrm{F}}_{j,s} p_{j,s} y_{j,s} \right) \\
&+ \begin{cases} \tau^{\mathrm{CO_2}}_s \varepsilon_s & \text{Intra-state Permit Trade} \\ \widetilde{\tau}^{\mathrm{CO_2}} (z_s - \varepsilon_s) & \text{Interstate Permit Trade} \end{cases} \qquad s \in \mathrm{RGGI} \\
&+ \tau^{\mathrm{Ele.}} P_{\mathrm{Ele.}} \left(c_{\mathrm{Ele.},s} + \sum_j x_{\mathrm{Ele.},j,s} \right) \quad s \in \mathrm{RGGI} \quad \perp \quad P^U_s, \quad \text{(IB)}
\end{aligned}
$$

where $k_{j,s} = (\kappa_{j,s} R / r_{j,s})^{\sigma^{KT}} A^K$, $l_{j,s} = (\gamma_{j,s} W_s / w_{j,s})^{\sigma^{LT}} A^L_s$, $c_{\mathrm{Ele.},s} = \left(\alpha_{\mathrm{Ele.},s} P^U_s / P_{\mathrm{Ele.}}\right)^{\sigma^C} U_s$ and $x_{\mathrm{Ele.},j,s} = (1 + \overline{\tau}^{Y,\mathrm{S}}_{j,s} + \overline{\tau}^{Y,\mathrm{F}}_{j,s}) \dfrac{\theta^{\sigma^E}_{\mathrm{Ele.},j,s}}{\theta_{E,j,s}} \left(\dfrac{p_{j,s}}{P_{\mathrm{Ele.}}(1 + \tau^{\mathrm{Ele.}})} \right)^{\sigma^E} y_{j,s}$. Qualifying emissions in each RGGI state are computed as the inner product of the electric sector's demand for fossil fuel inputs and the vector of corresponding emission factors:

$$
\varepsilon_s = \sum_e \phi_e \left[(1 + \overline{\tau}^{Y,\mathrm{S}}_{\mathrm{Ele.},s} + \overline{\tau}^{Y,\mathrm{F}}_{\mathrm{Ele.},s}) \frac{\theta^{\sigma^E}_{e,\mathrm{Ele.},s}}{\theta_{E,\mathrm{Ele.},s}} \left(\frac{p_{\mathrm{Ele.},s}}{P_e + \phi_e \tau^{\mathrm{CO_2}}_s} \right)^{\sigma^E} y_{\mathrm{Ele.},s} \right] \qquad s \in \mathrm{RGGI}
$$

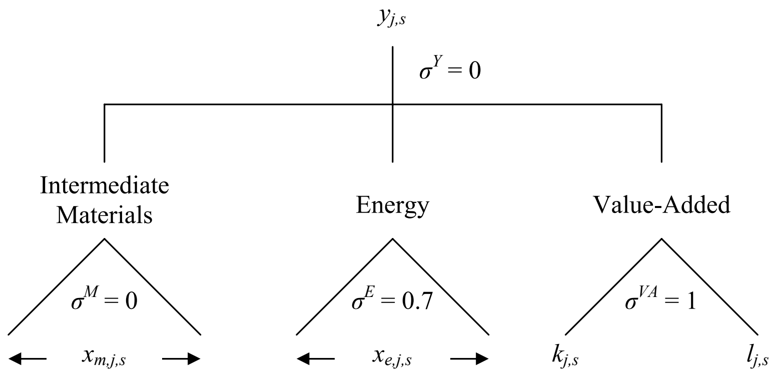
The variable P^U_s can be thought of as the vector of state-level consumer price indices. The numeraire price in the model is given by P^U_s in Washington DC; I therefore set the value of this element to unity and drop the corresponding income definition equation from the general equilibrium system.

General equilibrium

The excess demand correspondence of the economy is made up of the $(N \times S + N + 2S + 1)$-vector of zero profit conditions (ZP1)-(ZP5), the $(3(N \times S) + N + S + 1)$-vector of market clearance conditions (MC1)-(MC6), and the S income balance conditions (IB). The resulting mixed complementarity problem is a square system of $(4(N \times S) + 2(N + 1) + 4S)$ nonlinear equations, $\Upsilon(\mathbf{b})$, in $(4(N \times S) + 2(N + 1) + 4S)$ unknowns, $\mathbf{b} = \{p_{j,s}$, P_i, W_s, $w_{j,s}$, R, $r_{j,s}$,

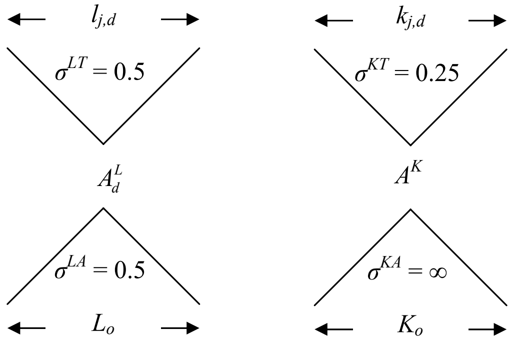
P_s^U, $y_{j,s}$, Y_i, A_s^L, A^K, $U_s\}$.

Figure 1: The Representation of Production and Imperfect Factor Mobility in the Model



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

(a) Industries' nested production functions



A^L_d = aggregate labor supply in destination state d; σ^{LA} = Elasticity of substitution among labor endowments of origin states o (K_o); σ^{LT} = Elasticity of transformation between aggregate and sector-specific labor at d ($l_{j,d}$); A^K = aggregate capital supply; σ^{KA} = Elasticity of substitution among origin states' capital endowments (K_o); σ^{KT} = Elasticity of transformation between aggregate and sector-specific capital ($k_{j,d}$).

(b) Imperfect interstate and intersectoral factor mobility

Figure 2: Benchmark Year-2004 Interregional Social Accounts (Billion $)

RGGI Participating States

	A	B	C	Fin. Use	Total
A	0.04	0.13	27.63	28.52	56.32
B	8.73	21.50	76.01	-77.72	28.52
C	9.42	5.12	1443.52	2384.06	3842.11
L	6.70	2.40	1270.29		1279.39
K	16.17	4.90	565.47		586.54
T	10.33	2.23	403.77		416.33
Total	51.40	36.27	3786.69	2334.86	6209.20

South

	A	B	C	Fin. Use	Total
A	0.07	2.37	48.80	42.27	93.51
B	33.09	173.52	87.70	59.43	353.74
C	18.09	72.92	2640.00	3533.50	6264.50
L	11.24	17.42	1845.32		1873.98
K	34.40	69.25	1264.50		1368.15
T	14.93	14.13	559.24		588.30
Total	111.83	349.59	6445.56	3635.20	10542.18

Midwest (incl. PA)

	A	B	C	Fin. Use	Total
A	0.06	0.54	41.14	36.10	77.83
B	12.30	62.66	69.21	-23.70	120.47
C	14.12	16.98	2348.51	3017.83	5397.43
L	10.32	6.89	1645.30		1662.51
K	23.86	14.38	929.00		967.24
T	13.59	4.66	495.39		513.64
Total	74.25	106.10	5528.55	3030.22	8739.12

West

	A	B	C	Fin. Use	Total
A	0.04	0.85	29.94	32.23	63.06
B	11.91	56.76	38.46	8.53	115.67
C	9.23	26.28	1639.16	2693.92	4368.59
L	7.16	8.23	1448.83		1464.22
K	14.75	25.65	551.14		591.54
T	10.16	8.66	404.30		423.12
Total	53.25	126.43	4111.83	2734.68	7026.19

A: Electric Power; B: Fossil Energy Sectors; C: Non-Energy Sectors; L: Labor; K: Capital; T: combined revenues from state and federal taxes on labor, capital and production.

Figure 3: Average Annual Growth Rates of State GDP and Energy Intensity, 2005-2015

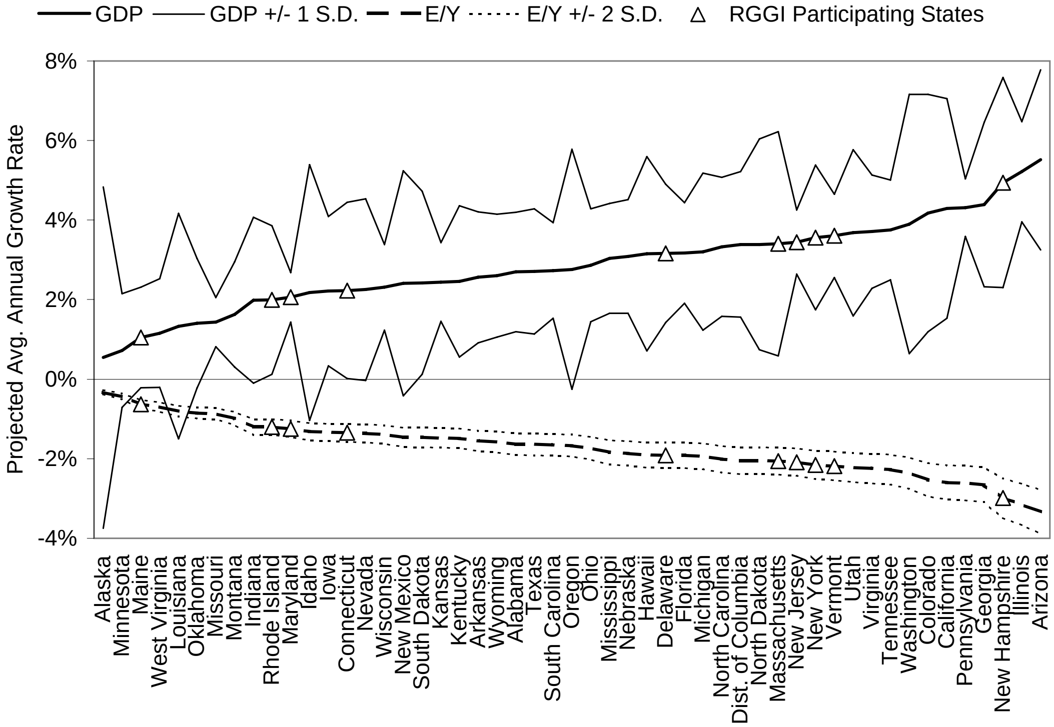


Table 1: RGGI State Electricity Trade and Emission Profiles

	2004 Ele. Import Share of Sales[a] (%)	2004 Ele. Sector Emissions[b] ($MTCO_2$)	Emissions Growth 1990 -2004[b] (%)	Projected 2015 Ele. Sector Emissions[c] ($MTCO_2$)	RGGI Allowance Allocation[d] ($MTCO_2$)
Connecticut	3.1	8.60	-0.4%	11.06	10.70 (B)
Maine	30.7	4.53	11.0%	30.60	5.95 (B)
New Hampshire	3.9	7.71	2.2%	3.65	8.62 (N)
Vermont	34.2	0.02	-1.3%	0.04	1.23 (N)
New York	3.6	52.98	-0.3%	59.25	64.31 (N)
New Jersey	0.0	18.90	3.4%	26.34	22.89 (B)
Delaware	0.0	5.91	-2.9%	10.37	7.56 (B)
Maryland	0.0	30.42	1.5%	37.39	37.50 (N)
Massachusetts	0.9	23.67	-0.3%	23.20	26.66 (N)
Rhode Island	3.8	1.96	5.7%	1.71	2.66 (N)
Subtotal	3.1	154.69	0.9%	203.61	188.08 (B)
Pennsylvania[e]	-0.1	116.51	0.8%	126.62	–
RGGI Total	2.3	271.20	0.9%	330.23	–

[a] EIA State Energy Data System.

[b] EPA State CO_2 Emissions from fossil fuel combustion in the electric power sector, 1990-2004 (`http://www.epa.gov/climatechange/emissions/state_energyco2inv.html`)

[c] Dynamic forecast for 2015 based on historical CO_2 emissions for each state's electricity sector (ε) using the ARIMA model $\log \varepsilon = \chi_0 + \chi_T \text{Year} + \sum_{\ell=0}^{2} \chi_\ell \log \mathcal{L}_\ell(\varepsilon)$, where $\mathcal{L}_\ell$ is the lag operator at lag length ℓ.

[d] (B) = allowance allocation projected to be binding, (N) = allowance allocation projected to be non-binding.

[e] Pennsylvania has not adopted an emission target but maintains observer status in RGGI.

Table 2: Results of the Analytical Model

(a) Algebraic Results

		Elasticity with respect to:			
		$\widehat{\varepsilon}_A$		$\widehat{\tau}_A^q$	
1. Carbon-energy	$\widehat{\xi}_A$	$-(1-\beta)/\Delta$	(–)	$[\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/(\alpha\Delta)$	(+)
price	$\widehat{\xi}_N$	$-(1-\beta)/\Delta$	(–)	$-[\alpha\delta + \sigma(1-\alpha)(1-\beta)]/(\alpha\Delta)$	(–)
2. Electricity	$\widehat{q}_A$	$[2\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/\Delta$	(+)	$\sigma(1-\alpha)[\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/(\alpha\Delta)$	(+)
output	$\widehat{q}_N$	$-(1-\beta)[\eta + \sigma(1-\alpha)]/\Delta$	(–)	$-[\eta + \sigma(1-\alpha)][\alpha\delta + \sigma(1-\alpha)(1-\beta)]/(\alpha\Delta)$	(–)
3. Electricity price	$\widehat{\pi}$	$-(1-\beta)/\Delta$	(–)	$-[\alpha\delta + \sigma(1-\alpha)(1-\beta)]/\Delta$	(–)
4. Electricity trade	$\widehat{t}$	$-(1-\beta)[\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/(\beta\Delta)$	(–)	$-[\alpha\delta + \sigma(1-\alpha)(1-\beta)]$ $\times[\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/(\alpha\beta\Delta)$	(–)
5. Carbon-energy	$\widehat{\varepsilon}_N$	$-\eta(1-\beta)/\Delta$	(–)	$-\eta[\alpha\delta + \sigma(1-\alpha)(1-\beta)]/(\alpha\Delta)$	(–)
demand	$\widehat{\mathcal{E}}$	$(1-\beta)[\alpha\delta + \sigma(1-\alpha)]/\Delta$	(+)	$-\eta(1-\beta)[\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/(2\alpha\Delta)$	(–)
6. Emission	$\widehat{\varepsilon}_A - \widehat{q}_A$	$\sigma(1-\alpha)(1-\beta)/\Delta$	(+)	$-\sigma(1-\alpha)[\alpha\delta + (1+\beta)(\eta + \sigma(1-\alpha))]/(\alpha\Delta)$	(–)
intensity	$\widehat{\varepsilon}_N - \widehat{q}_N$	$\sigma(1-\alpha)(1-\beta)/\Delta$	(+)	$\sigma(1-\alpha)[\alpha\delta + \sigma(1-\alpha)(1-\beta)]/(\alpha\Delta)$	(+)

$\Delta = 2\alpha\delta + \eta(1+\beta) + 2\sigma(1-\alpha) > 0$

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

		RGGI Only ($\widehat{\tau}_A^q = 0$)	RGGI With Border Measures ($\widehat{\tau}_A^q = \widehat{\tau}_{A,0}^q$)	Border Measures Only ($\widehat{\tau}_A^q = \widehat{\tau}_{A,0}^q$)
1. Carbon-energy	$\widehat{\xi}_A$	0.030	0.107	0.055
price	$\widehat{\xi}_N$	0.030	–	-0.052
2. Electricity	$\widehat{q}_A$	-0.059	-0.017	0.086
output	$\widehat{q}_N$	0.047	–	-0.081
3. Electricity price	$\widehat{\pi}$	0.009	–	-0.016
4. Electricity trade	$\widehat{t}$	1.768	–	-3.040
5. Carbon-	$\widehat{\varepsilon}_A$	-0.076[a]	-0.076[a]	0.055
energy	$\widehat{\varepsilon}_N$	0.030	–	-0.052
demand	$\widehat{\mathcal{E}}$	-0.021	-0.037	–
6. Emission	$\widehat{\varepsilon}_A - \widehat{q}_A$	-0.017	-0.060	-0.031
intensity	$\widehat{\varepsilon}_N - \widehat{q}_N$	-0.017	–	0.029
7. Leakage	Λ	0.420	–	1.005
8. No-leakage tax	$\widehat{\tau}_{A,0}^q$	0.032	0.032[a]	0.032[a]

[a] Exogenously imposed values.

Table 3: Sectors and Commodities in the CGE Model

A. Fossil Fuels

1. Coal
2. Petroleum
3. Gas

B. Non-Fossil Energy

4. Electric power
5. Crude oil & gas

C. Non-Energy

6. Energy-intensive manufacturing (Non-metallic minerals + Chemicals + Metals + Pulp & Paper)
7. Durable goods manufacturing
8. Non-Durable goods manufacturing
9. Transportation
10. Rest of the economy (Agriculture + Mining + Construction + Services + Government)

Table 4: Characteristics of the 2015 BAU Scenario

	Electric Power			CO_2 Emissions		Chg. / Ele. Producer Price	ASPI	P.C. ASPI
	Production (TWh)	Consumption (TWh)	Net Trade[a] (TWh)	Ele. Sector (MT)	Other Sectors (MT)	w.r.t. 2004 (%)	(Bn. 2004 $)	('000 2004 $)
Connecticut	42.8	44.7	-1.9	12.7	96.1	8.1	277.8	79.2
Delaware	11.1	16.5	-5.4	8.7	15.4	9.8	49.9	59.9
Maine	26.3	16.8	9.4	7.2	83.4	9.2	71.5	52.5
Maryland	72.6	94.2	-21.6	34.6	105.2	9.5	371.1	63.3
Massachusetts	66.7	78.6	-11.9	30.6	137.9	9.7	459.4	69.9
New Hampshire	33.3	15.2	18.1	9.8	52.5	9.6	81.6	59.4
New Jersey	75.2	107.7	-32.5	29.4	148.1	8.7	628.0	70.4
New York	193.8	202.7	-8.9	58.4	634.5	9.7	1271.2	67.2
Rhode Island	6.8	10.9	-4.1	3.5	25.6	9.4	63.9	59.7
Vermont	7.6	7.9	-0.3	0.0	28.8	9.4	33.5	50.7
RGGI	536.1	595.2	-59.1	194.9	1327.5	9.4	3307.9	67.4
Rest of US	5056.0	4395.2	660.8	2118.6	3433.8	9.9	13409.7	51.4

[a] Positive = exports; negative = imports.

Table 5: Impacts of RGGI Emission Targets

	Change in Electricity Market w.r.t. BAU			Chg. / CO_2 Emissions		Chg. / Ele. Producer	Chg. / P.C.	Allowance
	Production (%)	Consumption (%)	Net Trade[a] (%)	Ele. Sector (MT)	Other Sectors (MT)	Price w.r.t. BAU (%)	ASPI ($)	Price ($)
	A. Intra-state Allowance Trading							
Connecticut	-2.9	-0.2	58.5	-2.0	0.1	1.3	20.9	24
Delaware	-3.0	-0.2	5.7	-1.1	0.0	1.3	57.1	12
Maine	-13.3	-0.1	-36.9	-1.2	0.0	4.2	164.5	55
Maryland	0.2	-0.2	-1.8	0.1	0.1	0.5	-8.5	0
Massachusetts	-3.1	-0.2	16.2	-4.0	0.1	1.4	24.0	16
New Hampshire	-1.6	-0.2	-2.8	-1.2	0.0	1.0	49.5	13
New Jersey	-7.3	-0.1	16.5	-6.5	0.1	2.5	83.0	60
New York	0.3	-0.3	-11.7	0.2	0.3	0.5	-7.3	0
Rhode Island	-24.8	0.0	41.7	-0.9	0.0	8.0	265.9	147
Vermont	0.3	-0.3	-12.9	0.0	0.0	0.5	-3.3	0
RGGI	-2.7	-0.2	21.9	-16.6	0.8	1.2	28.6	–
Rest of US	0.3	-0.2	3.8	8.3	2.7	0.5	-6.8	–
	B. Interstate Allowance Trading							
Connecticut	-0.3	0.0	7.1	-0.5	0.0	0.2	1.8	2.8
Delaware	-0.7	0.0	1.5	-0.4	0.0	0.3	13.1	2.8
Maine	-0.6	0.0	-1.6	-0.1	0.0	0.2	7.8	2.8
Maryland	-0.5	0.0	1.5	-1.1	0.0	0.2	12.0	2.8
Massachusetts	-0.6	0.0	3.0	-1.1	0.0	0.2	4.2	2.8
New Hampshire	-0.4	0.0	-0.7	-0.4	0.0	0.2	11.4	2.8
New Jersey	-0.3	0.0	0.7	-1.1	0.0	0.2	2.1	2.8
New York	-0.3	0.0	6.2	-2.1	0.0	0.2	4.4	2.8
Rhode Island	-0.3	0.0	0.5	0.0	0.0	0.2	3.5	2.8
Vermont	0.0	0.0	-1.4	0.0	0.0	0.1	4.8	2.8
RGGI	-0.4	0.0	3.3	-6.8	0.1	0.2	5.1	2.8
Rest of US	0.1	0.0	0.6	2.2	1.0	0.1	-1.1	–
	C. Interstate Allowance Trading + Harmonized Zero-Leakage (2.5%) Electricity Tariff							
Connecticut	-0.5	-1.1	-14.6	-0.5	0.2	-0.1	8.0	2.7
Delaware	-0.8	-1.0	-1.2	-0.4	0.1	0.0	22.4	2.7
Maine	-0.7	-1.2	0.1	-0.1	0.1	0.0	13.7	2.7
Maryland	-0.6	-0.9	-2.1	-1.1	0.3	0.0	20.5	2.7
Massachusetts	-0.7	-1.0	-3.0	-1.1	0.4	0.0	9.9	2.7
New Hampshire	-0.5	-1.1	0.0	-0.4	0.1	-0.1	21.0	2.7
New Jersey	-0.4	-1.0	-2.2	-1.1	0.5	-0.1	8.1	2.7
New York	-0.4	-1.1	-15.7	-2.1	1.4	-0.1	11.1	2.7
Rhode Island	-0.4	-1.1	-2.1	0.0	0.1	-0.1	9.1	2.7
Vermont	-0.1	-1.1	-26.1	0.0	0.0	-0.2	10.3	2.7
RGGI	-0.5	-1.0	-5.8	-6.8	3.3	-0.1	11.8	2.7
Rest of US	-0.1	0.1	-0.9	0.1	-3.5	-0.2	-2.5	–

[a] Positive = exports; negative = imports.

Table 6: Impact of RGGI on Components of ASPI (% Change)

	Factor Income		Net	Recycled Revenue				Total
	Labor	Capital	Foreign Assets	Federal Taxes	State Taxes	Allow-ances[a]	Electricity Tariffs[a]	
	A. Intra-state Allowance Trading							
Connecticut	-0.10	-0.03	0.16	-0.03	-0.07	1.04	–	0.03
Delaware	-0.11	-0.03	-0.45	-0.03	-0.09	1.84	–	0.09
Maine	-0.23	-0.03	0.15	-0.03	-0.35	9.07	–	0.31
Maryland	-0.01	-0.03	0.14	-0.03	0.02	0.00	–	-0.01
Massachusetts	-0.08	-0.03	0.16	-0.03	-0.09	1.66	–	0.03
New Hampshire	-0.07	-0.03	0.14	-0.03	-0.05	1.53	–	0.08
New Jersey	-0.14	-0.03	0.18	-0.03	-0.20	3.65	–	0.12
New York	-0.01	-0.03	0.16	-0.03	0.02	0.00	–	-0.01
Rhode Island	-0.24	-0.03	0.16	-0.03	-0.65	15.92	–	0.44
Vermont	-0.01	-0.03	0.15	-0.03	0.02	0.00	–	-0.01
RGGI Total	-0.07	-0.03	0.16	-0.03	-0.06	1.32	–	0.04
	B. Interstate Allowance Trading							
Connecticut	-0.01	0.00	0.04	-0.01	-0.02	0.13	–	0.00
Delaware	-0.03	-0.01	-0.36	-0.01	-0.07	0.46	–	0.02
Maine	-0.01	0.00	0.03	-0.01	-0.10	0.52	–	0.01
Maryland	-0.01	0.00	0.02	-0.01	0.04	0.40	–	0.02
Massachusetts	-0.01	0.00	0.04	-0.01	-0.05	0.31	–	0.01
New Hampshire	-0.02	0.00	0.03	-0.01	-0.04	0.36	–	0.02
New Jersey	-0.01	-0.01	0.04	-0.01	-0.05	0.20	–	0.00
New York	-0.01	0.00	0.04	-0.01	0.02	0.16	–	0.01
Rhode Island	-0.01	0.00	0.04	-0.01	-0.10	0.38	–	0.01
Vermont	0.00	0.00	0.03	-0.01	0.09	0.00	–	0.01
RGGI Total	-0.01	0.00	0.03	-0.01	-0.01	0.22	–	0.01
	C. Interstate Allowance Trading + Harmonized Zero-Leakage (2.5%) Electricity Tariff							
Connecticut	-0.06	-0.04	0.08	-0.04	-0.06	0.13	0.51	0.01
Delaware	-0.07	-0.04	-0.34	-0.04	-0.10	0.45	0.57	0.04
Maine	-0.06	-0.04	0.07	-0.04	-0.13	0.51	0.93	0.02
Maryland	-0.05	-0.04	0.06	-0.04	0.00	0.39	0.83	0.03
Massachusetts	-0.06	-0.04	0.07	-0.04	-0.08	0.30	0.83	0.01
New Hampshire	-0.06	-0.04	0.06	-0.04	-0.08	0.35	0.63	0.03
New Jersey	-0.05	-0.04	0.09	-0.04	-0.08	0.20	0.78	0.01
New York	-0.06	-0.04	0.07	-0.04	-0.02	0.16	0.66	0.02
Rhode Island	-0.05	-0.04	0.07	-0.04	-0.13	0.37	1.19	0.01
Vermont	-0.05	-0.04	0.07	-0.04	0.05	0.00	0.45	0.02
RGGI Total	-0.06	-0.04	0.07	-0.04	-0.04	0.22	0.71	0.02

[a] Value of allowances expressed as a fraction of recycled revenue from pre-existing state taxes.

[b] Revenue generated by countervailing tariff on electric power in each state, recycled to the corresponding representative agent.

Table 7: Results of Sensitivity Analysis: RGGI Without Border Measures

	Chg. / Ele. Net Trade[a]	Chg. / Ele. CO_2 Intensity		Chg. / Armington Ele. Price	Change in CO_2 Emissions			Leakage					Allowance Price	Chg. / P.C. ASPI
		RGGI	Rest of U.S.		U.S. Net	RGGI Ele. Sector	RGGI Total	Internal	External Ele. Sector	External Non-Ele. Sector	U.S. Net	Λ		
	(%)	(%)	(%)	(%)	(MT)	(MT)	(MT)	(MT)	(MT)	(MT)	(MT)	(%)	($/ton)	($)
A. Base Case	3.3	-3.1	0.05	0.08	-3.4	-6.8	-6.7	0.1	2.2	1.0	3.4	49	2.8	5.1
B. Energy Intensity														
Ω = -0.51 (+2 S.D.)	7.6	-5.5	0.10	0.19	-6.1	-12.8	-12.6	0.2	4.6	1.9	6.7	53	6.2	11.2
Ω = -0.71 (-2 S.D.)	0.4	-0.5	0.01	0.01	-0.5	-1.0	-1.0	0.0	0.3	0.2	0.5	47	0.3	0.6
1% p.a. AEEI	20.1	-9.0	0.17	0.49	-9.4	-23.2	-22.7	0.6	10.0	3.2	13.9	60	15.3	26.6
0.5% p.a. AEEI	42.2	-11.4	0.22	1.00	-10.5	-34.4	-33.2	1.2	18.1	4.6	24.0	70	29.8	50.7
C. Avg. GSP Growth Rates														
+1 S.D.	10.6	-8.8	0.15	0.29	-10.3	-20.8	-20.5	0.4	6.9	3.3	10.6	51	10.1	17.6
-1 S.D.	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0
D. Interfuel Elasticities of Substitution														
$\sigma^E = 1.4$ (2 ×)	2.0	-3.6	0.09	0.04	-3.2	-7.5	-7.4	0.1	2.7	1.5	4.3	57	1.6	3.0
$\sigma^E = 0.35$ (0.5 ×)	6.0	-2.7	0.03	0.17	-3.3	-6.6	-6.5	0.1	2.5	0.7	3.3	50	5.3	9.4
E. Armington Elasticities of Substitution														
$\sigma^A_{\text{Elec.}} = 8$ (2 ×)	3.4	-3.0	0.05	0.08	-3.3	-6.6	-6.5	0.1	2.2	1.0	3.3	50	2.7	4.6
$\sigma^A_{\text{Elec.}} = 2$ (0.5 ×)	3.3	-3.3	0.06	0.09	-3.7	-7.1	-7.0	0.1	2.2	1.1	3.4	48	3.0	6.0
$2 \times \sigma^A_{e\neq\text{Elec.}}$	3.4	-3.1	0.05	0.08	-3.5	-6.9	-6.8	0.1	2.2	1.1	3.4	49	2.8	5.1
$0.5 \times \sigma^A_{e\neq\text{Elec.}}$	3.3	-3.1	0.05	0.08	-3.4	-6.7	-6.6	0.1	2.2	1.0	3.3	49	2.8	5.1

[a] Positive = exports; negative = imports.

Table 8: Results of Sensitivity Analysis: RGGI with Leakage-Neutralizing Electricity Tariffs

	Chg. / Ele. Net Trade[a]	Chg. / Ele. CO_2 Intensity		Chg. / Armington Ele. Price			Change in CO_2 Emissions			Leakage			Allowance Price	Chg. / P.C. ASPI
		RGGI	Rest of U.S.	RGGI	Rest of U.S.	Tariff	U.S. Net	RGGI Ele. sector	RGGI Total	Internal	External Ele. Sector	External Non-Elec. Sector		
	(%)	(%)	(%)	(%)	(%)	(%)	(MT)	(MT)	(MT)	(MT)	(MT)	(MT)	($/ton)	($)
A. Base Case	-5.8	-3.0	-0.04	2.36	-0.14	2.5	-6.9	-6.8	-3.5	3.3	0.1	-3.5	2.7	11.8
B. Energy Intensity														
Ω = -0.71 (+2 S.D.)	-10.1	-5.4	-0.09	4.56	-0.23	4.8	-12.8	-12.8	-6.5	6.3	0.5	-6.8	6.1	23.8
Ω = -0.51 (-2 S.D.)	-1.1	-0.5	-0.01	0.37	-0.03	0.4	-1.1	-1.0	-0.5	0.5	0.0	-0.6	0.3	1.7
1% p.a. AEEI	-16.9	-8.7	-0.23	9.33	-0.34	9.7	-23.3	-23.2	-10.4	12.9	1.3	-14.2	14.5	50.5
0.5% p.a. AEEI	-22.2	-11.0	-0.47	16.28	-0.36	16.7	-34.5	-34.4	-12.3	22.1	2.5	-24.8	27.7	88.7
C. Avg. GSP Growth Rates														
+1 S.D.	-14.2	-8.6	-0.15	6.74	-0.33	7.1	-21.0	-20.8	-10.2	10.7	0.8	-11.6	9.7	36.9
-1 S.D.	0.0	0.0	0.00	0.00	0.00	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D. Interfuel Elasticities of Substitution														
$\sigma^E = 1.4$ (2 ×)	-8.6	-3.5	-0.10	1.84	-0.16	2.0	-7.6	-7.5	-2.6	4.9	0.9	-6.0	1.6	8.4
$\sigma^E = 0.35$ (0.5 ×)	-3.7	-2.6	-0.02	3.29	-0.10	3.4	-6.6	-6.6	-4.2	2.4	-0.2	-2.2	5.1	18.2
E. Armington Elasticities of Substitution														
$\sigma^A_{\text{Elec.}} = 8$ (2 ×)	-5.3	-2.9	-0.04	2.26	-0.14	2.4	-6.6	-6.6	-3.5	3.1	0.2	-3.4	2.6	11.0
$\sigma^A_{\text{Elec.}} = 2$ (0.5 ×)	-6.1	-3.2	-0.03	2.36	-0.13	2.5	-7.2	-7.1	-3.8	3.3	0.1	-3.4	2.9	12.7
$2 \times \sigma^A_{e\neq\text{Elec.}}$	-5.5	-3.0	-0.04	2.27	-0.13	2.4	-6.8	-6.9	-3.7	3.1	0.2	-3.3	2.8	11.5
$0.5 \times \sigma^A_{e\neq\text{Elec.}}$	-5.5	-3.0	-0.04	2.26	-0.13	2.4	-6.8	-6.7	-3.6	3.1	0.2	-3.4	2.7	11.5

[a] Positive = exports; negative = imports.

References

Arellano, M. and S. Bond (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Review of Economic Studies 58*, 277–197.

Armington, P. S. (1969). A theory of demand for products distinguished by place of production. *IMF Staff Papers 16*, 159–176.

Babiker, M. H. (2001). Subglobal climate-change actions and carbon leakage: The implication of international capital flows. *Energy Economics 23*, 121–139.

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

Babiker, M. H. and T. F. Rutherford (2005). The economic effects of border measures in subglobal climate agreements. *Energy Journal 26*, 101–128.

Bolster, H. D. (2006). The commerce clause meets environmental protection: The compensatory tax doctrine as a defense of potential regional carbon dioxide regulation. *Boston College Law Review 47*, 772–737.

Burtraw, D., D. Kahn, and K. Palmer (2006). CO_2 allowance allocation in the Regional Greenhouse Gas Initiative and the effect on electricity investors. *Electricity Journal 19*, 79–90.

Copeland, B. R. and M. S. Taylor (2005). Free trade and global warming: a trade theory view of the Kyoto Protocol. *Journal of Environmental Economics and Management 49*, 205–234.

Farnsworth, D., C. Palmero, and C. Sherry (2007). Potential emissions leakage and the Regional Greenhouse Gas Initiative (RGGI): Evaluating market dynamics, monitoring options, and possible mitigation mechanisms—initial report of the RGGI Emissions Leakage Multi-State Staff Working Group. Technical report, Regional Greenhouse Gas Initiative.

Felder, S. and T. F. Rutherford (1993). Unilateral CO_2 reductions and carbon leakage: The consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management 25*, 162–176.

Fullerton, D. and G. E. Metcalf (2002). Tax incidence. In A. Auerbach and M. Feldstein (Eds.), *Handbook of Public Economics, vol. 4*, pp. 1787–1872. Elsevier.

Gerlagh, R. and O. Kuik (2007). Carbon leakage with international technology spillovers. Working Paper No. 2007-48, Fondazione Eni Enrico Mattei.

Jacoby, H. D. and A. D. Ellerman (2004). The safety valve and climate policy. *Energy Policy 32*, 481–491.

Metcalf, G. E. (2007). An empirical analysis of energy intensity and its determinants at the state level. *Energy Journal forthcoming.*

Nuclear Energy Agency/International Energy Agency (2005). *Projected Costs of Generating Electricity: 2005 Update.* Paris: OECD.

Stavins, R. N. (2006). A utility safety valve for cutting CO_2. *The Environmental Forum 23*, 14.

Sue Wing, I. (2005). The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting U.S. CO_2 emissions. *Energy Policy 34*, 3847–3869.

Sue Wing, I. (2007). The regional impacts of U.S. climate change policy: A general equilibrium analysis. mimeo, Boston University.

Sue Wing, I. and R. S. Eckaus (2007). The decline in U.S. energy intensity: Its origins and implications for long-run co_2 emission projections. *Energy Policy 35*, 5267–5286.

Weiner, J. B. (2007). Think globally, act globally: The limits of local climate policies. *University of Pennsylvania Law Review 155*, 1961–1979.