Limiting CO_2 Emissions in a Federal System: Understanding and Mitigating the Cost of U.S. Climate Policy at the State Level (Rough, Preliminary and Incomplete)

Ian Sue Wing [1]

Kennedy School of Government, Harvard University
Joint Program on the Science & Policy of Global Change, MIT
Center for Energy & Environmental Studies and Dept. of Geography & Environment, Boston University

Abstract

This paper investigates the state-level general equilibrium incidence of a national tradable permit scheme for limiting U.S. carbon dioxide (CO_2) emissions. It constructs an inter-regional computable general equilibrium model of the U.S. economy with 50 states and 10 industries, which is used to simulate the effects at the state and regional level of an economy-wide cap on CO_2 emissions. The results illustrate how the regional incidence of abatement costs in a national cap-and-trade system depends on the initial allocation of permits. This sheds light on states' incentives to support such a national policy, the distributional consequences of alternative rules for allocating emission allowances, and the characteristics of interstate transfer schemes to mitigate the economic losses in hardest-hit states. Such insights are crucial to the implementation of a meaningful U.S. climate policy.

Key words: Computable general equilibrium models, Carbon tax, Emission limits, Regional science, Interstate distribution
JEL Codes: C68, H23, H71, Q52, R13

1 Introduction

This paper examines the regional incidence within the U.S. of the costs of measures to mitigate climate change. The U.S. withdrawal from the Kyoto Protocol

[1] Address: Rm. 141, 675 Commonwealth Ave., Boston, MA 02215. Email: isw@bu.edu. Phone: (617) 353-4751. Fax: (617) 353-5986.

focused attention on what a feasible domestic policy to reduce greenhouse gas (GHG) emissions might look like, and has spawned a series of as yet unsuccessful legislative proposals for a nationwide cap-and-trade scheme. [2] However, all of these initiatives overlook the *geographic* dimension of the incidence of climate policy, which has important political economy issue because the elected representatives of individual states are the ones who ultimately produce the legislation implementing a national emissions cap. Viewed in the context of Congress' redistributive role, the uphill battle faced these proposals is symptomatic of the classic collective action problem: individual lawmakers' have private incentives to avoid the incidence of abatement costs falling on their own constituents. The most basic empirical data necessary to come to grips with this issue is the structure of payoffs, namely, the distribution of the economic costs of climate policy among the states. This paper takes a first cut at developing the relevant estimates.

Few studies specifically address the geographic dimension of the incidence of climate policy at the sub-national level. We therefore have only a limited understanding of either the incentives faced by different states to support or oppose such policy, or the feasibility of transfer schemes to mitigate adverse impacts in hardest-hit states. [3] Here we show how the gross costs of a national policy to abate carbon dioxide (CO_2) emissions are distributed at the state level, as a first step toward understanding the economic incentives faced by states to support a limit on national emissions.

Such results are of tremendous importance to the design and implementation of climate change policies in federal political systems. Concentrated political op-

[2] The most prominent of these are the McCain-Lieberman/Gilchrest-Olver Climate Stewardship Act (S.139/H.R.4067) and the Bingaman-Domenici Climate and Economy Insurance Act (amendment to H.R.6, the Energy Policy Act of 2005). The former would cap GHG emissions at 1990 levels by the year 2010. The latter would specify annual emission limits sufficient to reduce the U.S. economy's emission intensity of GDP by 2.4 percent per year from 2010-2019, with a "safety-valve" provision to issue additional allowances to cap the marginal cost of abatement at \$7/ton CO_2. There are two quite separate proposals at the sub-national level: the California GHG emission reduction targets (EO S-3-05, which would return that state's emissions to year-2000 levels by 2010), and the Regional Greenhouse Gas Initiative in CT, DE, ME, NH, NJ, NY and VT (which would stabilize CO_2 emissions from electricity generation , at year-2005 levels from 2009-2015).

[3] Petchey and Levtchenkova (2003) report a general dearth of analysis of the regional incidence of national taxes. With respect to the climate issue, Balistreri and Rutherford (2004) estimate the interstate distribution of the reductions in gross state product which would have resulted from the U.S. Kyoto commitment, while Ross et al. (2004) examine the economic effects of regional initiatives to reduce GHG emissions. Closest to the spirit of present study, Rose and Zhang (2004) estimate the costs of CO_2 abatement in ten U.S. regions which result from a national cap-and-trade system under different rules for allocating emission allowances.

position to a cap-and-trade system is likely to closely track the severity of deadweight economic losses which are localized in particular sub-national jurisdictions. This mirrors the collective action problem of agreements to reduce GHG emissions at the international level, which has by now been thoroughly investigated (Eckaus et al., 1997; Rose et al., 1998). The main insight of that literature is that the distribution of welfare burdens is fundamentally driven by the allocation of rights to pollute, and is also strongly influenced by income and substitution effects.

Regarding income effects, it is well known that the incidence of a tax falls most heavily on immobile factors of production (McLure, 1971). The implications of this principle are most easily seen in the case of fossil fuel extraction and processing activities. These are often tied to completely immobile geologic deposits, so that the incidence of a binding cap on CO_2 emissions will tend to fall disproportionately on the regions where such activities are concentrated. The key empirical issue is how much the emission limit reduces demand for the output of fossil fuel producers in each region, and with it their demands for these fixed factors of production. This is of particular concern for coal-intensive states in the West and Appalachia, given that fuel's high carbon content.

More generally, labor and capital employed by polluting (here, fossil fuel *using*) firms are also imperfectly mobile in the short run, across both economic sectors and geographic space. In a tradable permits scheme the initial allocation of allowances determines the total cost of abatement faced by each pollution source. Thus, the distribution of permits among sectors and regions will affect the returns to the labor and capital hired by energy intensive producers. The empirical question here is how much the cost of abatement warranted by a particular allowance allocation increases firms' marginal cost of production and reduces the demand for the factors of production in each region. As before, the regional incidence of the policy will be strongly influenced by the geographic concentration of fossil-fuel intensive firms.

The substitutability of fuels with different carbon intensities, and of non-energy goods for fuel, mediates how an emission tax affects industries' factor demands and households' commodity expenditures. Substitution governs the increase an industry's cost of production in response to a given amount of abatement, and how this effect translates into a decline in households' final demand and downstream firms' intermediate demands for that industry's output, a reduction in its factor demands, and—as wages and rental rates adjust to clear factor markets–a reallocation of labor and capital among industries. The homogeneity of the U.S. domestic market, with its high elasticities of interstate export supply and import demand, implies that an important additional consequence will be the reallocation of production among states. Prior research on climate policy-induced industry movements among countries (Babiker et al., 2000) and sub-national regions (Balistreri and Rutherford, 2004) suggests that the effect on factor returns at the state level may be large.

The standard tool for sorting out these effects and analyzing their macroeconomic consequences in a consistent manner is the computable general equilibrium (CGE) simulation. The vast majority of general equilibrium analyses of climate policies focus on the aggregate economy as the unit of analysis. Interregional CGE (ICGE), models have been developed which elucidate the incidence of these policies' gross costs at the sub-national level, but they have typically disaggregated the U.S. economy down to the level of census regions or an individual state. [4] The contribution of the present study is to construct an ICGE model which captures the general equilibrium impacts of abatement across *all* states simultaneously, and which is able to characterize the incidence of the costs of CO_2 abatement at the state level. The results shed light on the question of regional incidence discussed above, and advance our understanding of both the incentives faced by different states to support a national cap on CO_2 emissions, and the interstate distributional consequences of alternative schemes for allocating emission allowances.

The remainder of the paper is organized into three sections. Section 2 presents the structure of the ICGE model, briefly describes the construction of the benchmark dataset, and outlines the calibration of the model's baseline. The simulation results are presented and discussed in Section 3, which analyzes the drivers of emissions and income in the baseline no-policy case, investigates the effects of emission taxes set at levels around the safety-valve envisioned by the Bingaman-Domenici Act, and explores the redistributive consequences of different rules for allocating tradable emission permits among the states. Section 4 concludes.

2 Model, Data and Calibration

2.1 The structure of the model

The ICGE model is a static spatial price equilibrium simulation of the U.S. economy based on the prototype in Sue Wing and Anderson (forthcoming). Its struc-

[4] A large, mostly older literature employs interregeional and single-state CGE models in regional economic analysis (see, e.g., Partridge and Rickman, 1998). We will not say more about this work here. Li and Rose (1995) examine the effect of an emission limit on a single state, modeled as a small open economy. Balistreri and Rutherford and Ross et al. perform similar analyses using models which resolve one state but aggregates the remainder of the economy into the five census regions, and explicitly represent interregional trade in goods and services. By contrast, Rose and Zhang use a partial equilibrium model based on marginal abatement cost curves, which does not capture the consequences of either income or substitution effects for welfare losses.

Table 1
Sectors and Commodities in the CGE Model

A. Fossil Fuels	*C. Non-Energy Goods/Sectors*
1. Coal	6. Energy-intensive sectors (Stone, clay & glass + Chemicals + Metals + Pulp & Paper)
2. Petroleum	7. Durable goods manufacturing
3. Gas	8. Non-Durable goods manufacturing
B. Non-Fossil Energy Goods/Sectors	9. Transportation
4. Electric power	10. Rest of the economy (Agriculture + Mining + Construction + Services + Government)
5. Crude oil & gas	

ture is deliberately simple, dividing the U.S. economy into 50 states and the District of Columbia, indexed by $s = \{1,\dots,S\}$ and ten profit-maximizing industries (shown in Table 1), indexed by $j = \{1,\dots,N\}$, each of which produces a single homogeneous commodity which we index by $i = \{1,\dots,N\}$. 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 ($k_{j,s}$) and labor ($l_{j,s}$) and an N-vector of intermediate inputs ($x_{i,j,s}$). Industries' technology is represented by a simple bi-level production function in which output is modeled as a constant elasticity of substitution (CES) function of intermediate goods and a Cobb-Douglas aggregate of k and l. The dual of output is the producer price ($p_{j,s}$), defined as the unit cost of production plus indirect business taxes ($\overline{\tau}_{j,s}$).

Households in each state are modeled as a utility-maximizing representative agent with Cobb-Douglas preferences over her consumption of commodities ($c_{i,s}$). Consumption is financed by income, which redounds to each state agent from the rental to industries of labor L_s and capital K_s, with which she is endowed.

Interstate trade is modeled very simply, using the Armington (1969) assumption. Aggregate supply of the i^{th} good (Y_i) is generated an Armington CES composite of state varieties, which enables the demands for each commodity by industries and households in all states to be fulfilled at a single, national market-clearing price (P_i) which is a weighted average of the s producer prices. Market clearance is given by:

$$Y_i = \sum_s \left(c_{i,s} + \sum_j x_{i,j,s} \right) \quad \perp \quad P_i,$$

where the symbol "$\perp$" indicates the duality between a variable and its associated general equilibrium condition.

A key feature of the model is that factors are mobile across states and industries, but imperfectly so.[5] The main implication is that $L_s \neq \sum_j l_{j,s}$ and $K_s \neq \sum_j k_{j,s}$. There is an economy-wide capital market in which all states supply capital at an aggregate rental rate (R). Frictions in capital reallocation are modeled as the symmetric opposite of goods trade—by treating the demands for capital by industries in each state as a constant elasticity of transformation (CET) disaggregation of the aggregate supply. Labor markets are geographically segmented, which allows wages to differ by state (W_s). In general, production in a given state also draws labor from surrounding jurisdictions. We represent this phenomenon using a CET-CES function, modeling industries' demands for labor in each state as a constant elasticity of transformation (CET) disaggregation of the total labor supply, which is itself a CES composite of own-supplied and neighboring states' labor. The upshot is that within each industry and state, l and k are quasi-fixed inputs with differentiated prices ($w_{j,s}$ and $r_{j,s}$), whose intersectoral and interstate movement is determined by the elasticities of factor substitution and transformation.

At the state level, an emission tax ($\tau_s^{\mathrm{CO_2}}$) is represented as a commodity-specific markup on the prices of fossil fuels, where the markup varies with each fuel's carbon content. The latter is represented by constant emission factors (ϕ_e) which translate a unit economic quantity of each fossil fuel into a different quantity of $\mathrm{CO_2}$.[6] The gross-of-tax consumer price of fossil fuels is then given by $P_e + \phi_e \tau_s^{\mathrm{CO_2}}$.

Government is not explicitly represented in the model. Each state agent levies indirect business taxes and carbon taxes on the industries within her jurisdiction, the revenue from which supplement factor income. Carbon taxes are the price dual of quantitative limits on emissions (z_s), which represent the allocation of emission rights to each state. A cap on emissions in a particular state implies a limit on that jurisdiction's total *use* (*not* production) of fossil fuels:

$$\mathscr{E}_s \leq z_s \quad \perp \quad \tau_s^{\mathrm{CO_2}}.$$

where $\mathscr{E}_s = \sum_e \varepsilon_{e,s}$ denotes total emissions and $\varepsilon_{e,s} = \phi_e \left(c_{e,s} + \sum_j x_{e,j,s}\right)$ represents emissions by fuel. A cap-and-trade system is simulated by a dropping the state subscript on the carbon tax variable, and letting the model solve for the unique market-clearing price which is consistent with the economy-wide cap ($Z = \sum_s z_s$):

$$\sum_s \mathscr{E}_s \leq Z \quad \perp \quad \tau^{\mathrm{CO_2}}.$$

At the cost-minimizing optimum, states choose their levels of abatement to equalize their marginal costs of emission control at ($\tau_s^{\mathrm{CO_2}} = \tau^{\mathrm{CO_2}}$). This marginal cost,

[5] Cf. international CGE models, in which the standard assumption is that primary factors are completely immobile among countries, but completely mobile among sectors.
[6] ϕ_e is simply the ratio of aggregate emissions from fuel e to the aggregate use of that fuel.

and the associated dual vector of emission levels ($\mathscr{E}_s$), depend solely on the aggregate limit Z. However, the interstate distribution of the total cost of abatement will depend on the vector of permit allocations z_s.

This is apparent from the necessary divergence between value-added (i.e., gross state product: GSP) and income (i.e., annual state personal income: ASPI) created by the structure of taxes and factor demands:

$$\text{GSP}_s = \sum_s \left(w_{j,s} l_{j,s} + r_{j,s} k_{j,s} \right) \tag{1}$$

$$\text{ASPI}_s = (W_s L_s + R K_s) + TR_s + CTR_s \tag{2}$$

where $TR_s = \sum_j \overline{\tau}_{j,s} p_{j,s} y_{j,s}$ represents revenue from indirect business taxes and $TR_s = \tau_s^{\text{CO}_2} \mathscr{E}_s$ is the revenue from a tax on CO_2. ASPI is the measure of each state's economic welfare in the model, whose change in response to emission limits is pseudo-equivalent variation (PEV).[7] Eq. (2) makes clear that the change in welfare due to an emission tax depends on three factors: the direct effect of the tax on factor returns (in parentheses), the "revenue-recycling" effect (CTR) and the "tax-interaction" effect, whereby $\tau_s^{\text{CO}_2}$ may raise or lower TR.

2.2 Data development

Official data on state social accounting matrices (SAMs) are not published by the Bureau of Economic Analysis (BEA). We therefore employed available state-level data from BEA on personal income and value added, energy consumption data from DOE/EIA (2003c,b) and emission data from Blasing et al. (2004) to disaggregate BEA's national input-output (I-O), value-added and final demand accounts for the year 2000.[8] The result is a consistent set of interregional social accounts, which form the calibration point for the model outlined above. Below we give a brief description of our methods, which build on Sue Wing and Anderson (forthcoming).

Our starting point is the aggregate SAM for the U.S. economy in the year 2000 described in Sue Wing (2005). We first disaggregate the factor demand account, allocating the labor and capital returns and indirect business tax revenues of each industry the national SAM among the states. This was done separately for each

[7] Strictly speaking, equivalent variation is a *consumption*-based measure. However, because data constraints prevent us from resolving the components of final use at the state level, we attribute the income applied to *all* final uses to households' welfare.

[8] The full set of state-level SAMs, with consistent interstate trade flow matrices is estimated by IMPLAN, but the cost of these data is prohibitive. A somewhat similar dataset has been constructed from official statistics by Randall W. Jackson and co-authors (Jackson, 1998), but is not available in the form necessary for the present analysis. Investigating the use of these data is a priority for future research.

component of GSP in each industry, computing each state's share of the sum of that component across all states (e.g., compensation in industry j and state s as a share of the sum across all states of compensation in j, with the same procedure for gross operating surplus and tax payments) and multiplying by the corresponding component of value added for that industry in the national SAM.

We next disaggregate intermediate input, using the simplifying assumption that the production technology in a given industry is the same for all states with respect of intermediate commodity uses. For each industry (column) of the national I-O table, we expressed the share of each intermediate commodity use (row) as a share of value added. We then multiplied the resulting vector of shares by each state's value added in that industry computed in the previous step, to yield the set of intermediate demands at the state level.

A fundamental constraint on the construction of the interregional social accounts was the need to match published data on the geographic distribution of CO_2 emissions from the use of different fossil fuels. Intermediate demands for fuels in key energy-intensive industries were therefore adjusted to be consistent with published estimates of state-level uses of coal, petroleum and natural gas by industry group DOE/EIA (2003c,b), by using these data to allocate states' shares of each fuel in each of the corresponding industries.

The need for accurate CO_2 accounting also constrained our estimates of final use by commodity. We first estimated final uses of coal, petroleum and natural gas by dividing Blasing et al.'s (2004) estimates of states' CO_2 from each fuel by the corresponding emission factor, to yield gross state consumption. Subtracting the gross intermediate use of each fuel estimated in the prior step then yielded each state's final uses, while the difference between a state's gross output and gross consumption of each fuel gave its net exports to other states and the rest of the world.

Our procedure to disaggregate final uses of non-fossil energy commodities and non-energy goods was very simple. We first estimated state's gross income by dividing total final demand in the aggregate SAM according to each state's shares of the sum of ASPI across all states in 2000. We then subtracted states' gross final expenditure on fossil fuels estimated in the previous step, to yield estimates of gross non-fuel expenditures. Our last step was to apportion the final uses of non-fossil energy commodities and non-energy goods in the national SAM according to each state's residual expenditure share of the sum of residual expenditures across all states.

Our final step was to estimate states' primary factor endowments. This task was complicated by the lack of official data on states' factor supplies, and the gap between states' factor supplies and their industries's factor demands as a conse-

Fig. 1. Benchmark Interregional Social Accounts for 2000 (Bn $)

Northeast	A	B	C	Fin. Use	Total
A	5	3	22	17	47
B	22	0	27	15	64
C	11	13	1,422	2,136	3,582
Lab.	3	9	1,297		1,309
Cap.	5	19	718		742
Tax	1	5	80		87
Total	47	50	3,566	2,168	5,830

Midwest	A	B	C	Fin. Use	Total
A	8	6	28	11	53
B	24	1	30	15	69
C	12	15	1,613	2,156	3,795
Lab.	4	10	1,339		1,353
Cap.	5	20	697		722
Tax	1	6	81		88
Total	53	58	3,788	2,182	6,081

South	A	B	C	Fin. Use	Total
A	24	14	41	59	138
B	57	21	40	22	139
C	31	61	2,154	3,125	5,371
Lab.	9	22	1,886		1,916
Cap.	14	44	1,070		1,129
Tax	3	12	136		151
Total	138	175	5,326	3,206	8,844

West	A	B	C	Fin. Use	Total
A	10	5	24	35	74
B	32	6	27	15	81
C	17	23	1,565	2,218	3,823
Lab.	4	10	1,369		1,383
Cap.	9	20	827		856
Tax	2	6	81		88
Total	74	70	3,893	2,269	6,306

U.S.	A	B	C	Fin. Use	Total
A	46	27	115	122	311
B	134	29	123	67	353
C	71	113	6,753	9,635	16,573
Lab.	20	51	5,891		5,962
Cap.	33	104	3,312		3,449
Tax	7	29	377		414
Total	311	353	16,573	9,824	27,062

A. Fossil Fuels; B. Non-Fossil Energy Sectors; C. Non-Energy Sectors

quence of interstate labor and capital mobility.[9] The only data available on interstate factor movements were the 2000 Census county-to-county worker flow files, which we aggregated up to the state level. The resulting matrix of origin-destination flows was used in conjunction with BEA data on states' employment and average wages to compute the share of labor compensation ($\lambda_{o,d}$) in each destination state (d) paid to commuters from other origin states (o). We then estimated the labor endowment of each states s as its own industries' demand for labor minus its labor imports from other origins plus its labor exports to other destinations:

$$L_s = A_s^L - \sum_{o \neq s} \lambda_{o,s} A_o^L + \sum_{d \neq s} \lambda_{s,d} A_d^L,$$

where $A_\omega^L = \sum_j l_{j,\omega}$ denotes the total demand for labor by industries in state ω. We then calculated each state's endowment of capital as the residual after subtracting its labor endowment from its gross income.

The final benchmark social accounts are shown in Figure 1, aggregated to the level of census regions.

[9] Labor compensation in BEA's state regional economic profiles corresponds to employment by industries in each state, not the earnings of that state's residents. This was a problem for geographically small jurisdictions such as Washington DC—a large proportion of whose labor demand is supplied by Maryland and Virginia, the New England states and Hawaii.

2.3 Calibration

Profit maximization by industries and utility maximization by the representative agents result in vectors of demands for commodities and factors, which are functions of goods and factor prices, industries' activity levels and the agents' income levels. The model is specified in a complementarity format, in which the general equilibrium of the economy is posed as a vector of market clearance, zero-profit and income balance equations (Scarf, 1973; Mathiesen, 1985a,b; Rutherford, 1987). The model's algebraic structure results from substituting the demand functions into these equilibrium conditions to yield a square system of nonlinear inequalities which defines the aggregate excess demand correspondence of the economy (Sue Wing, 2004). See Appendix A for details. The excess demand correspondence is formulated as a mixed complementarity problem (MCP), numerically calibrated using the MPSGE subsystem for GAMS (Rutherford 1999; Brooke et al 1998), and solved using the PATH solver (Dirkse and Ferris, 1995). The model replicates the economic conditions in both the benchmark SAM and the regional accounts, and closely matches the vector of state-level emissions in Blasing et al. (2004).

Emission limits commencing in the year 2010 are a common feature of the legislative proposals described in the introduction. Therefore, to be policy-relevant the no-policy counterfactual solution of the model should reflect the economic conditions likely to prevail at that point in time. Accordingly, we constructed the model's business-as-usual (BAU) baseline by scaling the economic flows in the year-2000 benchmark according to projections of fossil fuel emissions and GDP based on historical series. We assumed that each state's GSP would continue to expand at its average annual rate of growth over the period 1994-2004, and scaled up its endowments of labor and capital to match. We assumed that states' emissions intensities would continue to evolve at the rates of growth they exhibited from 1994-2001, and scaled down the coefficients on fossil fuel inputs in industries' cost functions and state agents' expenditure functions to be consistent with these trends. In the baseline run, GDP is $13.4 trillion, closely matching DOE/EIA (2003a), while the economy emits 7,180 MT of CO_2, well above EIA's estimate of 6,365 MT.

3 Results

3.1 The baseline economy in 2010

Table 2 illustrates key economic characteristics of the states in the BAU simulation. Columns 1 and 5 illustrate states' economic importance in terms of both production (GSP) and income (ASPI). The results highlight the difference between eqs. (1) and (2), with the latter exceeding the former in the majority of states and at the level of the macroeconomy. Nevertheless, the two measures of size closely track one another, with California, New York and Texas being largest according to both criteria, and the smallest being N. Dakota, Vermont and Wyoming in terms of production, and Alaska, N. Dakota, and Wyoming in terms of income. Column 2 shows that states exhibit very different rankings when their economic importance is expressed in terms of their wealth, or per capita income. The richest states are Connecticut, Washington DC and Massachusetts, while the poorest are W. Virginia, Louisiana and Mississippi, with a dispersion of 35 percent around the national average income of $47,362.

Columns 3 and 6 tabulate the CO_2 emissions generated in states' production and consumption of fossil fuels. The two measures of dirtiness differ markedly—while the dirtiest states in absolute terms are Texas and California using either criterion, the cleanest states in absolute terms are Rhode Island, Washington DC and Vermont from when measured from the consumption side and Hawaii, Vermont and South Dakota measured from the production side. Moreover, the results for the macroeconomy indicate that the U.S. in 2010 is a net CO_2 importer, which is due primarily to its consumption of foreign petroleum.

Columns 4 and 7 compute states' CO_2 emission intensity from the consumption and the production side, with the former dividing emissions from fossil fuel use in Column 3 by income in Column 1, and the latter dividing emissions embodied in states' fossil-fuel production in Column 6 by GSP in Column 5. While the majority dirtiness of consumption and production are very different in most states, both criteria indicate that CO_2 intensity is highest in Wyoming and W. Virginia. However, the least dirty states in terms of production are S. Carolina, Arizona and Washington DC, while in terms of consumption are New York, Connecticut and Massachusetts.

The two measures above exhibit a high degree of dispersion, with the emission intensities of the cleanest and and dirtiest states differing by a factor of 16 in consumption and over 400 in production! The reason is the highly skewed interstate distribution of production in energy sectors, which is summarized in Columns 8-10. Louisiana, Alaska and Mississippi are most intensive in petroleum production, while Kentucky, W. Virginia and Wyoming have largest shares of value-added in coal mining. However, the latter states, as well as Montana and S. Carolina, are also relatively intensive in the production of electricity, especially using coal-fired generation. This circumstance, combined with the fact these states are relatively poor, explains why their CO_2 intensity from consumption of fossil-fuels is also relatively high. Finally, given that the bulk of abatement in response to an economy-wide tax on CO_2 will likely come from reductions in coal use by the electric power sector (Sue Wing, 2005), coal- and electricity-intensive states are the bellwether for the economic impacts of emission limits.

Table 2: Key State Characteristics of the 2010 Pre-Tax Equilibrium

	1. ASPI		2. ASPI per capita		3. CO_2 (Fossil Fuel Cons.)		4. Intensity (Fuel Cons.)		5. GSP		6. CO_2 (Fossil Fuel Prod.)		7. Intensity (Fuel Prod.)		8. Coal GSP Shr.		9. Elec. GSP Shr.		10. Oil GSP Shr.	
	Bn $	Rank	000$	Rank	MT	Rank	kg/$	Rank	Bn $	Rank	MT	Rank	kg/$	Rank	%	Rank	%	Rank	%	Rank
AL	164	24	37	44	171	14	1.04	11	153	25	161	12	1.06	10	0.22	8	1.90	13	0.33	18
AK	26	50	42	31	69	36	2.64	4	26	48	26	35	1.00	12			0.83	49	1.40	2
AZ	247	18	48	17	110	23	0.45	35	231	19	14	40	0.06	50			1.22	36	0.01	41
AR	91	33	34	48	79	33	0.86	14	86	34	53	27	0.62	15			1.85	14	0.63	9
CA	1855	1	55	10	462	2	0.25	48	1830	1	676	2	0.37	23			0.93	48	0.40	14
CO	239	20	55	8	99	28	0.41	38	230	20	138	18	0.60	17	0.16	10	1.16	42	0.09	27
CT	217	23	64	1	53	41	0.25	49	204	23	25	36	0.12	36			1.13	44	0.09	28
DE	41	44	52	14	18	47	0.45	33	48	42	4	46	0.08	46			1.33	32		
DC	36	45	63	2	11	50	0.32	45	82	35	3	48	0.04	51			0.64	50	0.02	40
FL	774	4	48	16	314	4	0.41	39	630	4	65	24	0.10	38			1.22	37	0.07	32
GA	373	12	45	23	191	12	0.51	29	392	9	49	30	0.12	34			1.19	39	0.07	33
HI	50	42	41	34	23	45	0.46	32	51	41	3	49	0.07	48			1.50	26		
ID	56	40	43	28	23	44	0.42	37	52	40	5	45	0.10	40			1.76	15		
IL	578	5	46	20	265	8	0.46	31	561	5	295	8	0.53	18	0.05	14	1.57	22	0.38	16
IN	248	17	41	35	294	5	1.18	7	240	17	149	15	0.62	16	0.08	12	1.61	20	0.27	19
IA	121	30	41	33	109	24	0.89	13	114	29	15	38	0.13	33			1.49	27		
KS	112	32	41	32	83	32	0.75	18	106	32	55	26	0.52	19			1.67	16	0.39	15
KY	154	26	38	42	214	10	1.39	6	148	26	474	5	3.20	5	0.84	3	1.42	30	0.22	22
LA	138	28	31	50	268	7	1.94	5	143	28	516	4	3.62	3	0.02	19	2.50	5	3.37	1
ME	50	41	39	39	27	43	0.54	27	45	45	6	44	0.13	32			1.60	21	0.07	31
MD	294	15	55	7	97	29	0.33	42	246	16	52	29	0.21	27	0.03	16	1.56	24	0.08	29
MA	389	10	61	3	94	31	0.24	50	379	10	46	32	0.12	35			1.19	40	0.08	30
MI	405	9	41	36	209	11	0.51	28	375	11	71	23	0.19	30			1.54	25	0.13	25
MN	258	16	52	13	112	22	0.43	36	249	15	62	25	0.25	26			0.99	47	0.26	20
MS	87	35	31	51	100	27	1.15	9	78	36	75	21	0.96	13			2.29	7	1.20	3
MO	226	22	40	37	161	17	0.71	19	218	22	74	22	0.34	25	0.05	13	1.32	33	0.16	23

Table 2: (Continued)

	1. ASPI		2. ASPI per capita		3. CO_2 (Fossil Fuel Cons.)		4. Intensity (Fuel Cons.)		5. GSP		6. CO_2 (Fossil Fuel Prod.)		7. Intensity (Fuel Prod.)		8. Coal GSP Shr.		9. Elec. GSP Shr.		10. Oil GSP Shr.	
	Bn $	Rank	000$	Rank	MT	Rank	kg/$	Rank	Bn $	Rank	MT	Rank	kg/$	Rank	%	Rank	%	Rank	%	Rank
MT	33	46	36	45	38	42	1.16	8	27	47	90	20	3.38	4	0.54	6	2.92	3	1.17	4
NE	73	36	42	29	58	39	0.80	17	69	37	6	43	0.09	43			1.20	38		
NV	113	31	56	6	64	38	0.56	24	111	31	10	41	0.09	42			1.46	28	0.04	37
NH	70	37	56	5	23	46	0.33	43	65	38	7	42	0.10	39			1.61	19	0.03	39
NJ	499	7	59	4	153	19	0.31	46	453	7	226	9	0.50	21			1.44	29	0.60	10
NM	65	38	36	47	73	34	1.12	10	65	39	146	16	2.25	7	0.61	5	2.17	9	0.43	13
NY	1040	2	55	9	252	9	0.24	51	1024	2	152	14	0.15	31			1.10	46	0.14	24
NC	360	13	45	25	183	13	0.51	30	366	12	42	33	0.11	37			1.27	35	0.06	34
ND	25	51	39	41	66	37	2.65	3	23	49	53	28	2.28	6	0.70	4	2.29	8		
OH	457	8	40	38	278	6	0.61	22	447	8	161	13	0.36	24			1.64	18	0.36	17
OK	125	29	36	46	115	21	0.92	12	111	30	117	19	1.05	11			1.94	11	1.17	5
OR	159	25	46	21	57	40	0.36	40	171	24	14	39	0.08	45			1.13	45	0.04	38
PA	557	6	45	24	326	3	0.59	23	503	6	437	6	0.87	14	0.20	9	2.04	10	0.24	21
RI	49	43	47	18	13	49	0.27	47	47	43	4	47	0.08	47			1.66	17		
SC	153	27	38	43	102	25	0.67	20	143	27	28	34	0.20	29			2.81	4	0.04	36
SD	32	47	43	27	18	48	0.55	25	31	46	2	51	0.06	49			1.38	31		
TN	242	19	42	30	161	18	0.66	21	235	18	47	31	0.20	28	0.02	18	0.50	51	0.11	26
TX	976	3	47	19	807	1	0.83	16	951	3	1013	1	1.06	9	0.05	15	2.35	6	0.91	6
UT	88	34	39	40	73	35	0.83	15	93	33	179	10	1.93	8	0.45	7	1.56	23	0.86	8
VT	28	48	46	22	9	51	0.32	44	23	50	2	50	0.09	44			1.91	12		
VA	374	11	53	12	169	15	0.45	34	358	13	164	11	0.46	22	0.11	11	1.17	41	0.05	35
WA	295	14	50	15	100	26	0.34	41	275	14	140	17	0.51	20	0.02	17	1.14	43	0.54	12
WV	61	39	34	49	165	16	2.72	2	46	44	540	3	11.76	2	3.36	2	4.51	2	0.54	11
WI	237	21	44	26	129	20	0.55	26	222	21	21	37	0.09	41			1.27	34		
WY	26	49	53	11	95	30	3.61	1	21	51	352	7	16.86	1	4.94	1	5.11	1	0.88	7
U.S.	13367	0	47	0	7186	0	0.54	0	12795	0	7066	0	0.55	0	0.06		1.43		0.33	

3.2 The general equilibrium incidence of CO_2 taxes

We first develop intuition for how the state economies behave in response to emission constraints. This was done by investigating the impacts of a tax on emissions set at different levels, centered around the safety-valve limit in the Bingaman-Domenici proposal of \$7/ton CO_2.

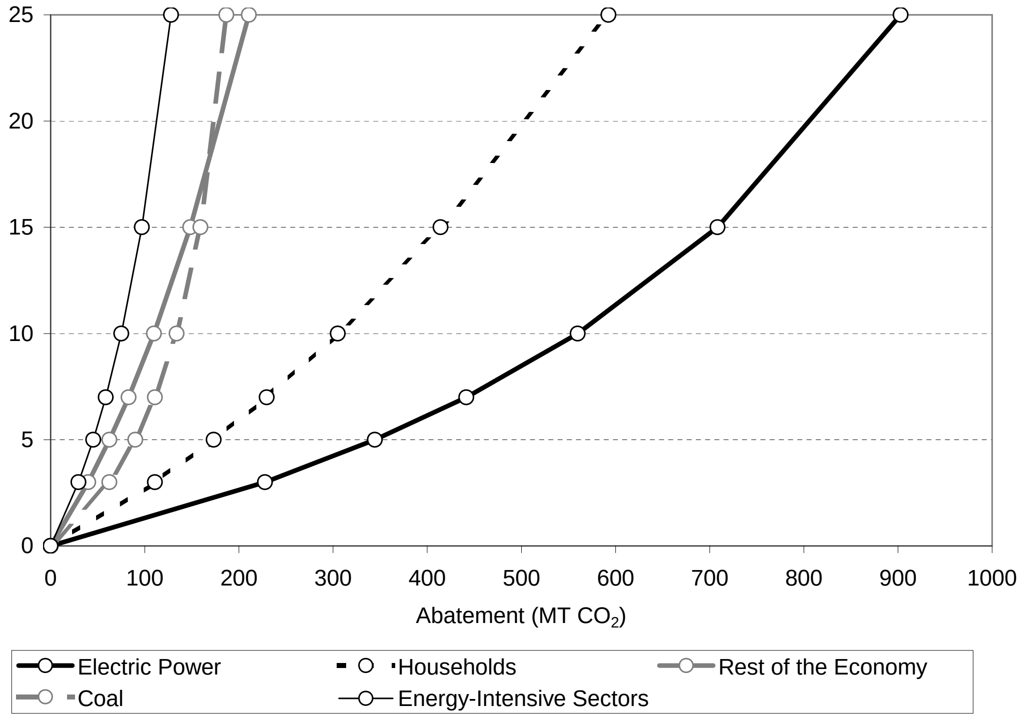
We begin by illustrating the reduction in emissions from fossil fuel consumption in response to the tax in the form of marginal abatement cost (MAC) schedules which are aggregated up to the level of industries, shown in Figure 2. The simulation results suggest that aggregate emissions would decline by 7 percent in response to a tax of \$3/ton, 15 percent in response to the Bingaman-Domenici \$7/ton tax, and 25 percent from a \$15/ton tax. As in previous results for the U.S. (Sue Wing, 2004, 2005), the bulk of abatement comes from reductions in fossil fuel consumption by electricity generators and households, with somewhat smaller reductions emanating from the fossil-fuel, energy-intensive and service and agriculture sectors, and very little abatement being produced by manufacturing, transportation or fuel mining. The implication is that states with relatively shares of coal and electricity in value added have more low-cost abatement opportunities and will therefore respond more elastically to the tax.

This intuition is borne out by the interstate patterns of CO_2 abatement. As the data are too numerous to plot MAC curves for each state, we tabulate the percentage reductions in emissions associated with the fossil fuels consumed and produced in each state, using the estimates in Columns 3 and 6 of Table 2 as a baseline. The results are shown in Table 3, which summarizes the percentage change in emissions from the production and the consumption of fossil fuels. While there are significant differences in states' rankings under the two criteria, by either measure, vigorous abatement is concentrated in the relatively coal-intensive states (Kentucky, W. Virginia and N. Dakota), while the least abatement occurs in small states which lack significant fossil fuel or electric power production (Washington DC, Vermont, Rhode Island and Hawaii).

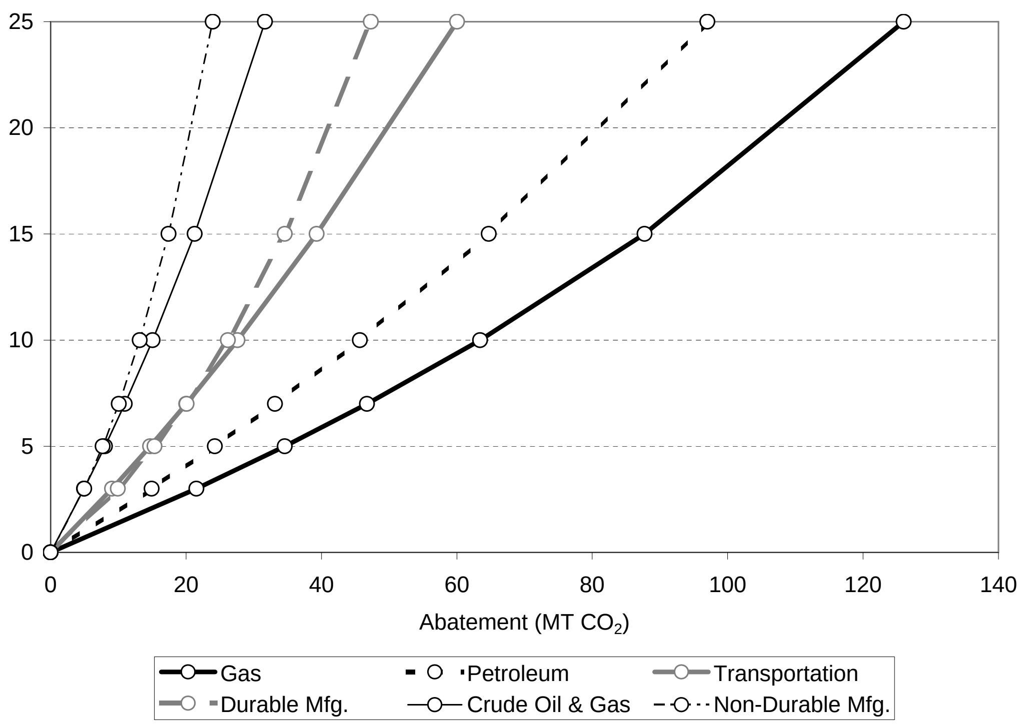
Table 4 illustrates the economic impact of the tax on households, summarizing the percentage change in welfare and the absolute change in per capita ASPI relative to the baseline in Columns 1 and 2 of Table 2. The economic effects are generally small, with tax causing a very slight increase in aggregate welfare. This result is due to tax interactions, whereby the welfare gain from the income effect of revenue from the tax offsets the welfare loss from the substitution effect associated with pre-existing taxes on industries. We take up this issue in more detail below.

States' rankings under both welfare criteria are almost identical, with the tax precipitating the largest welfare losses in Connecticut, New York and Califor-

Fig. 2. Industry Marginal Abatement Cost Curves for the U.S. Economy in 2010



(a) Large abaters



(b) Small abaters

Table 3
Abatement Response to a Tax

	1. % Abatement (Fuel Prod.)					Rank[a]	% Abatement (Fuel Cons.)					Rank[a]
	3	5	7	10	15		3	5	7	10	15	
AL	-12	-18	-23	-30	-38	7	-11	-16	-21	-26	-34	7
AK	-4	-6	-8	-10	-14	21	-8	-12	-15	-20	-26	22
AZ	-1	-2	-3	-3	-5	45	-7	-10	-13	-17	-22	30
AR	-3	-5	-7	-10	-14	26	-8	-13	-16	-21	-27	17
CA	-3	-5	-6	-9	-12	32	-3	-5	-6	-9	-12	48
CO	-10	-16	-20	-25	-32	9	-7	-10	-14	-18	-23	28
CT	-2	-3	-4	-6	-8	41	-4	-6	-7	-10	-14	45
DE	-3	-5	-7	-9	-13	28	-4	-7	-9	-12	-17	38
DC	-1	-1	-1	-2	-2	48	-3	-4	-6	-8	-11	51
FL	-2	-4	-5	-7	-10	38	-5	-8	-11	-15	-19	35
GA	-2	-4	-5	-7	-10	36	-7	-11	-15	-19	-25	24
HI	0	1	1	1	2	51	-4	-6	-8	-11	-15	42
ID	-3	-5	-6	-9	-13	30	-4	-6	-9	-12	-16	40
IL	-7	-11	-14	-18	-24	15	-7	-11	-14	-18	-24	25
IN	-10	-15	-20	-25	-32	10	-11	-17	-21	-27	-35	5
IA	-3	-5	-7	-9	-13	27	-9	-14	-18	-23	-30	14
KS	-2	-4	-6	-8	-11	34	-9	-14	-18	-23	-30	13
KY	-16	-24	-31	-38	-48	1	-15	-22	-28	-35	-44	4
LA	-5	-8	-11	-15	-22	17	-6	-10	-14	-19	-25	27
ME	-2	-4	-5	-7	-10	37	-3	-5	-7	-9	-13	47
MD	-6	-10	-12	-16	-20	16	-6	-10	-13	-16	-22	31
MA	-2	-3	-4	-5	-7	42	-4	-6	-7	-10	-14	44
MI	-3	-5	-6	-9	-13	29	-7	-10	-13	-17	-23	29
MN	-3	-4	-6	-9	-12	33	-6	-9	-12	-16	-21	32
MS	-3	-5	-7	-10	-14	25	-8	-12	-16	-21	-27	18
MO	-8	-13	-16	-21	-27	12	-10	-15	-19	-24	-31	10
MT	-13	-20	-25	-32	-40	5	-11	-16	-20	-25	-32	9
NE	-3	-5	-7	-10	-14	22	-10	-16	-20	-26	-33	8
NV	-1	-2	-3	-4	-6	44	-6	-9	-12	-16	-21	33
NH	-1	-2	-2	-3	-5	46	-5	-7	-10	-13	-17	37
NJ	-2	-4	-5	-7	-10	35	-4	-7	-9	-12	-16	39
NM	-11	-17	-21	-27	-35	8	-10	-14	-19	-24	-30	11
NY	-2	-3	-4	-6	-8	40	-3	-5	-7	-10	-14	46
NC	-2	-3	-4	-6	-9	39	-8	-12	-16	-20	-26	20
ND	-14	-22	-27	-35	-43	3	-17	-26	-33	-41	-50	1
OH	-3	-5	-6	-9	-13	31	-8	-12	-16	-20	-26	19
OK	-3	-5	-7	-10	-14	23	-8	-12	-16	-20	-26	21
OR	-3	-6	-8	-11	-15	20	-4	-6	-8	-10	-14	43
PA	-10	-15	-19	-24	-31	11	-8	-13	-16	-21	-27	16
RI	0	-1	-1	-1	-1	50	-3	-4	-6	-8	-12	50
SC	-2	-3	-3	-5	-7	43	-9	-13	-17	-21	-27	15
SD	-1	-1	-2	-2	-3	47	-6	-9	-12	-15	-20	34
TN	-8	-12	-16	-21	-28	13	-11	-16	-21	-26	-34	6
TX	-5	-8	-10	-14	-19	18	-5	-8	-11	-15	-20	36
UT	-8	-12	-16	-21	-26	14	-9	-14	-18	-23	-30	12
VT	0	-1	-1	-1	-1	49	-3	-5	-6	-9	-13	49
VA	-14	-21	-27	-34	-42	4	-8	-12	-15	-20	-25	23
WA	-4	-7	-9	-12	-16	19	-4	-6	-8	-11	-15	41
WV	-15	-23	-29	-36	-45	2	-17	-25	-32	-39	-49	2
WI	-3	-5	-7	-10	-14	24	-7	-11	-14	-19	-24	26
WY	-13	-19	-25	-31	-39	6	-16	-24	-30	-37	-46	3
U.S.	-8	-12	-15	-19	-25		-7	-11	-15	-19	-25	

[a] Ranking at $\tau_s^{CO_2}$ = \$7/ton

nia, but actually generating substantial welfare *gains* in Wyoming, N. Dakota and Louisiana! In these states, a tax of \$7/ton increases households' annual income by more than half a percent, which translates into additional income of over \$40 per person in N. Dakota and Louisiana, and over \$100 per person in Wyoming.

Table 4
Response of Income and Welfare

	Chg. in per-capita ASPI ($)					Rank[a]	Pseudo-Equivalent Variation (%)					Rank[a]
	3	5	7	10	15		3	5	7	10	15	
AL	24	38	51	67	90	12	0.07	0.10	0.14	0.18	0.24	11
AK	86	130	166	211	270	3	0.20	0.31	0.40	0.50	0.64	4
AZ	-1	-4	-8	-16	-32	34	0.00	-0.01	-0.02	-0.03	-0.07	34
AR	30	46	59	76	98	9	0.09	0.13	0.17	0.22	0.28	7
CA	-24	-41	-59	-85	-128	50	-0.04	-0.08	-0.11	-0.15	-0.23	51
CO	-17	-29	-42	-62	-96	47	-0.03	-0.05	-0.08	-0.11	-0.17	47
CT	-24	-42	-59	-87	-133	51	-0.04	-0.07	-0.09	-0.14	-0.21	49
DE	14	20	24	27	28	23	0.03	0.04	0.05	0.06	0.06	23
DC	3	2	-1	-9	-26	32	0.01	0.00	0.00	-0.01	-0.04	32
FL	-6	-12	-18	-30	-51	39	-0.01	-0.02	-0.04	-0.06	-0.11	38
GA	9	13	14	14	10	25	0.02	0.03	0.03	0.03	0.02	25
HI	8	11	12	12	8	28	0.02	0.03	0.03	0.03	0.02	27
ID	-2	-5	-9	-17	-32	35	0.00	-0.01	-0.02	-0.04	-0.07	35
IL	-6	-12	-19	-29	-48	40	-0.01	-0.03	-0.04	-0.06	-0.10	40
IN	44	69	91	121	162	6	0.11	0.17	0.22	0.29	0.39	6
IA	26	39	50	62	76	13	0.06	0.09	0.12	0.15	0.18	13
KS	21	31	39	47	56	16	0.05	0.07	0.09	0.11	0.13	16
KY	12	25	40	65	107	15	0.03	0.07	0.11	0.17	0.29	15
LA	90	141	187	249	338	2	0.29	0.45	0.60	0.80	1.08	2
ME	16	24	30	36	43	20	0.04	0.06	0.08	0.10	0.11	20
MD	-15	-26	-39	-59	-94	46	-0.03	-0.05	-0.07	-0.11	-0.17	45
MA	-23	-40	-57	-83	-127	49	-0.04	-0.06	-0.09	-0.13	-0.21	48
MI	7	9	9	8	3	30	0.02	0.02	0.02	0.02	0.01	29
MN	-4	-9	-15	-26	-48	36	-0.01	-0.02	-0.03	-0.05	-0.09	36
MS	46	71	94	123	163	5	0.15	0.23	0.31	0.40	0.53	5
MO	14	20	25	29	32	22	0.03	0.05	0.06	0.07	0.08	21
MT	12	21	30	44	65	19	0.03	0.06	0.08	0.12	0.18	18
NE	33	50	65	83	105	7	0.08	0.12	0.15	0.19	0.25	9
NV	16	23	27	30	28	21	0.03	0.04	0.05	0.05	0.05	24
NH	-10	-19	-28	-44	-72	42	-0.02	-0.03	-0.05	-0.08	-0.13	41
NJ	-14	-24	-36	-55	-88	45	-0.02	-0.04	-0.06	-0.10	-0.15	44
NM	26	40	53	70	93	10	0.07	0.11	0.15	0.20	0.26	10
NY	-23	-39	-55	-81	-123	48	-0.04	-0.07	-0.10	-0.15	-0.23	50
NC	9	11	13	12	8	27	0.02	0.03	0.03	0.03	0.02	28
ND	71	118	164	232	344	4	0.18	0.30	0.42	0.59	0.88	3
OH	13	19	23	26	28	24	0.03	0.05	0.06	0.06	0.07	22
OK	18	27	33	39	44	17	0.05	0.07	0.09	0.11	0.12	17
OR	-6	-11	-18	-29	-50	38	-0.01	-0.02	-0.04	-0.06	-0.11	39
PA	0	-1	-3	-7	-15	33	0.00	0.00	-0.01	-0.01	-0.03	33
RI	-14	-24	-35	-52	-82	44	-0.03	-0.05	-0.07	-0.11	-0.17	46
SC	23	35	45	56	70	14	0.06	0.09	0.12	0.15	0.19	14
SD	7	9	10	8	1	29	0.02	0.02	0.02	0.02	0.00	30
TN	8	11	13	13	11	26	0.02	0.03	0.03	0.03	0.03	26
TX	31	47	60	77	98	8	0.07	0.10	0.13	0.17	0.21	12
UT	16	25	32	41	51	18	0.04	0.06	0.08	0.10	0.13	19
VT	-9	-16	-23	-36	-59	41	-0.02	-0.03	-0.05	-0.08	-0.13	42
VA	-6	-11	-16	-25	-42	37	-0.01	-0.02	-0.03	-0.05	-0.08	37
WA	-11	-20	-29	-44	-71	43	-0.02	-0.04	-0.06	-0.09	-0.14	43
WV	5	25	53	102	194	11	0.02	0.08	0.17	0.33	0.62	8
WI	5	6	5	2	-7	31	0.01	0.01	0.01	0.00	-0.02	31
WY	132	231	333	487	740	1	0.28	0.48	0.70	1.02	1.55	1
U.S.	3	3	1	-3	-12		0.01	0.01	0.00	-0.01	-0.03	

[a] Ranking at $\tau_s^{CO_2}$ = $7/ton

By contrast, the magnitude of households' welfare losses in the hardest-hit states by the tax is small: no more than one-tenth of one percent for a $7/ton tax, for a reduction in income of less than $20 per person.

Table 5
Response of Value Added and Tax Revenue

	Chg. in GSP (%)					Rank[a]	CO_2 Tax Revenue Share of ASPI (%)					Rank[a]
	3	5	7	10	15		3	5	7	10	15	
AL	-0.26	-0.42	-0.57	-0.78	-1.09	41	0.28	0.44	0.58	0.77	1.03	11
AK	-0.91	-1.47	-2.01	-2.78	-3.95	49	0.73	1.16	1.55	2.09	2.89	2
AZ	-0.09	-0.15	-0.21	-0.30	-0.44	19	0.12	0.20	0.27	0.37	0.52	35
AR	-0.17	-0.28	-0.39	-0.54	-0.78	36	0.24	0.37	0.50	0.68	0.93	15
CA	-0.09	-0.14	-0.20	-0.28	-0.41	14	0.07	0.12	0.16	0.23	0.33	48
CO	-0.14	-0.23	-0.31	-0.43	-0.62	30	0.12	0.18	0.25	0.34	0.48	39
CT	-0.06	-0.10	-0.15	-0.21	-0.31	10	0.07	0.12	0.16	0.22	0.32	49
DE	-0.05	-0.09	-0.13	-0.18	-0.28	5	0.13	0.22	0.29	0.41	0.58	31
DC	-0.05	-0.08	-0.11	-0.16	-0.25	3	0.09	0.15	0.21	0.29	0.42	43
FL	-0.09	-0.15	-0.21	-0.29	-0.43	15	0.12	0.19	0.25	0.35	0.49	38
GA	-0.10	-0.17	-0.23	-0.32	-0.47	21	0.14	0.23	0.30	0.41	0.58	29
HI	-0.06	-0.10	-0.14	-0.20	-0.29	7	0.13	0.21	0.29	0.41	0.58	32
ID	-0.06	-0.10	-0.15	-0.21	-0.31	9	0.12	0.20	0.27	0.37	0.53	36
IL	-0.12	-0.20	-0.28	-0.38	-0.56	27	0.13	0.20	0.27	0.37	0.52	33
IN	-0.28	-0.46	-0.62	-0.85	-1.20	43	0.31	0.49	0.64	0.85	1.14	9
IA	-0.21	-0.35	-0.47	-0.66	-0.94	37	0.24	0.38	0.51	0.68	0.94	14
KS	-0.17	-0.28	-0.38	-0.53	-0.77	35	0.20	0.32	0.42	0.57	0.78	18
KY	-0.41	-0.63	-0.83	-1.10	-1.47	45	0.36	0.55	0.71	0.91	1.18	6
LA	-0.70	-1.13	-1.54	-2.12	-3.01	48	0.54	0.86	1.15	1.56	2.14	5
ME	-0.05	-0.08	-0.11	-0.16	-0.24	4	0.16	0.26	0.35	0.49	0.70	23
MD	-0.09	-0.15	-0.21	-0.29	-0.43	16	0.09	0.15	0.20	0.28	0.39	45
MA	-0.06	-0.10	-0.14	-0.20	-0.30	8	0.07	0.11	0.16	0.22	0.31	51
MI	-0.11	-0.18	-0.25	-0.35	-0.52	25	0.14	0.23	0.31	0.42	0.59	28
MN	-0.10	-0.17	-0.23	-0.33	-0.48	22	0.12	0.20	0.26	0.36	0.51	37
MS	-0.23	-0.37	-0.51	-0.72	-1.03	39	0.32	0.50	0.67	0.91	1.25	7
MO	-0.17	-0.28	-0.38	-0.52	-0.74	34	0.19	0.30	0.40	0.54	0.73	19
MT	-0.36	-0.57	-0.76	-1.02	-1.40	44	0.31	0.49	0.65	0.87	1.18	8
NE	-0.17	-0.27	-0.37	-0.51	-0.73	33	0.21	0.33	0.44	0.59	0.80	17
NV	-0.10	-0.16	-0.23	-0.32	-0.47	20	0.16	0.25	0.35	0.47	0.67	24
NH	-0.06	-0.09	-0.13	-0.19	-0.28	6	0.09	0.15	0.21	0.28	0.40	44
NJ	-0.08	-0.13	-0.18	-0.26	-0.38	13	0.09	0.15	0.20	0.28	0.40	46
NM	-0.41	-0.65	-0.87	-1.17	-1.63	46	0.31	0.48	0.64	0.86	1.18	10
NY	-0.07	-0.12	-0.17	-0.23	-0.35	12	0.07	0.11	0.16	0.22	0.32	50
NC	-0.11	-0.17	-0.24	-0.34	-0.49	24	0.14	0.22	0.30	0.41	0.56	30
ND	-0.73	-1.14	-1.50	-1.99	-2.66	47	0.65	0.98	1.24	1.56	1.94	4
OH	-0.13	-0.22	-0.30	-0.42	-0.61	29	0.17	0.26	0.36	0.48	0.67	22
OK	-0.28	-0.45	-0.62	-0.86	-1.23	42	0.25	0.40	0.54	0.73	1.01	12
OR	-0.07	-0.11	-0.15	-0.22	-0.32	11	0.10	0.17	0.23	0.32	0.46	40
PA	-0.16	-0.25	-0.35	-0.47	-0.67	31	0.16	0.26	0.34	0.46	0.64	25
RI	-0.04	-0.07	-0.10	-0.15	-0.22	2	0.08	0.13	0.18	0.25	0.36	47
SC	-0.10	-0.17	-0.24	-0.33	-0.48	23	0.18	0.29	0.39	0.53	0.73	20
SD	-0.09	-0.15	-0.21	-0.30	-0.44	17	0.16	0.25	0.34	0.47	0.66	26
TN	-0.17	-0.27	-0.37	-0.50	-0.71	32	0.18	0.28	0.37	0.49	0.66	21
TX	-0.23	-0.37	-0.51	-0.71	-1.01	38	0.24	0.38	0.52	0.71	1.00	13
UT	-0.26	-0.41	-0.56	-0.76	-1.06	40	0.23	0.36	0.48	0.64	0.87	16
VT	-0.04	-0.06	-0.08	-0.12	-0.18	1	0.09	0.15	0.21	0.29	0.42	42
VA	-0.12	-0.19	-0.27	-0.37	-0.53	26	0.13	0.20	0.27	0.37	0.51	34
WA	-0.09	-0.15	-0.21	-0.30	-0.44	18	0.10	0.16	0.22	0.30	0.43	41
WV	-1.23	-1.89	-2.47	-3.20	-4.22	50	0.72	1.08	1.38	1.75	2.22	3
WI	-0.13	-0.21	-0.28	-0.40	-0.58	28	0.15	0.24	0.33	0.44	0.62	27
WY	-1.82	-2.81	-3.67	-4.80	-6.37	51	1.01	1.52	1.95	2.48	3.18	1
U.S.	-0.14	-0.23	-0.32	-0.44	-0.63		0.15	0.24	0.32	0.43	0.60	

[a] Ranking at $\tau_s^{CO_2}$ = \$7/ton

Table 5 sheds light on the origins this result, summarizing the changes in GSP and recycled carbon tax revenues which result from the tax. In all states industries as a whole are worse off, with reductions in GSP mirroring the intensity of abatement—and, ultimately, the shares of coal, petroleum and especially elec-

Table 6
Response of Components of Income

	Chg. in Pc. Factor Income ($)				Chg. in Pc. Pre-Existing Tax Rev. ($)				Chg. in Pc. CO_2 Tax Rev. ($)			
	5	7	10	Rank[a]	5	7	10	Rank[a]	5	7	10	Rank[a]
AL	-110	-145	-193	30	-14.5	-19.2	-25.6	44	162	214	284	11
AK	-293	-400	-549	51	-55.4	-75.7	-104.7	48	485	652	879	2
AZ	-101	-140	-196	23	-1.5	-2.1	-3.1	20	96	130	177	35
AR	-77	-106	-146	2	-3.9	-5.4	-7.5	29	128	172	232	19
CA	-102	-143	-202	27	0.3	0.4	0.4	14	65	89	124	49
CO	-127	-174	-242	47	-6.4	-8.4	-11.1	34	102	138	189	32
CT	-121	-168	-238	45	3.4	4.6	6.3	2	74	101	140	46
DE	-101	-141	-201	24	2.2	2.8	3.8	7	109	148	205	23
DC	-110	-155	-223	38	11.0	14.9	20.5	1	96	133	185	34
FL	-104	-144	-202	28	-1.4	-2.0	-2.9	19	90	122	167	38
GA	-91	-125	-174	11	-2.5	-3.5	-4.9	24	103	138	188	31
HI	-87	-121	-172	7	1.5	2.0	2.7	10	89	121	168	39
ID	-96	-133	-188	16	2.2	3.0	4.1	6	84	115	159	42
IL	-102	-139	-193	22	-3.6	-4.7	-6.2	27	95	128	174	36
IN	-119	-156	-206	39	-13.8	-18.5	-24.9	43	201	266	351	6
IA	-116	-158	-216	41	-6.9	-9.4	-13.0	35	160	213	286	12
KS	-93	-127	-174	12	-7.5	-10.3	-14.3	36	133	177	237	18
KY	-138	-172	-209	46	-45.6	-58.7	-75.1	47	205	265	342	7
LA	-101	-138	-189	21	-10.0	-13.8	-19.1	41	269	362	488	5
ME	-86	-120	-172	6	1.3	1.8	2.3	11	101	139	193	30
MD	-111	-154	-216	35	-0.8	-1.1	-1.5	18	83	112	153	43
MA	-115	-159	-225	42	2.4	3.3	4.5	5	70	96	133	48
MI	-84	-116	-162	4	-1.8	-2.6	-3.7	21	94	127	173	37
MN	-109	-151	-212	33	-1.9	-2.7	-3.8	22	103	139	191	29
MS	-73	-100	-138	1	-5.2	-7.2	-10.0	33	153	206	278	13
MO	-96	-129	-176	13	-8.0	-10.9	-14.9	37	122	163	217	20
MT	-110	-146	-195	32	-43.4	-55.6	-70.5	46	178	236	315	9
NE	-91	-122	-165	8	-4.3	-5.9	-8.2	31	142	189	251	16
NV	-121	-167	-236	44	-2.0	-2.9	-4.2	23	143	194	265	15
NH	-110	-154	-216	34	1.6	2.2	2.9	8	85	116	160	41
NJ	-111	-154	-218	36	0.8	1.1	1.4	13	85	116	160	40
NM	-108	-144	-194	29	-23.7	-31.5	-42.2	45	172	229	307	10
NY	-104	-145	-205	31	1.5	2.0	2.7	9	63	86	120	50
NC	-89	-122	-170	9	-2.6	-3.6	-5.2	25	100	134	181	33
ND	-206	-244	-274	48	-66.1	-87.7	-116.4	49	384	488	613	3
OH	-85	-116	-161	5	-3.0	-4.1	-5.8	26	107	144	195	27
OK	-104	-142	-197	25	-10.2	-14.0	-19.4	42	147	198	267	14
OR	-96	-133	-189	17	2.7	3.6	4.9	4	78	108	149	45
PA	-114	-155	-212	37	-4.2	-5.4	-7.0	30	116	155	210	22
RI	-89	-124	-176	10	1.2	1.7	2.3	12	61	84	118	51
SC	-80	-109	-151	3	-0.2	-0.4	-0.7	15	111	148	200	24
SD	-103	-142	-200	26	-0.4	-0.5	-0.9	16	108	146	201	25
TN	-100	-134	-181	19	-8.4	-11.3	-15.4	39	118	156	207	21
TX	-116	-161	-226	43	-8.2	-11.2	-15.5	38	177	240	329	8
UT	-99	-133	-180	15	-10.2	-13.5	-18.0	40	139	186	249	17
VT	-95	-132	-187	14	3.1	4.1	5.7	3	70	97	135	47
VA	-115	-157	-216	40	-5.5	-7.1	-9.3	32	105	141	191	28
WA	-96	-134	-189	18	-0.6	-0.8	-1.2	17	80	109	151	44
WV	-227	-270	-309	49	-94.6	-120.8	-152.8	50	342	437	554	4
WI	-100	-137	-191	20	-3.8	-5.2	-7.3	28	107	144	196	26
WY	-331	-391	-440	50	-179.3	-230.7	-295.5	51	733	944	1207	1
U.S.	-105	-144	-200		-5.0	-6.7	-9.0		113	152	206	

[a] Ranking at $\tau_s^{CO_2}$ = $7/ton

tricity in value-added. However, the beneficial effects of recycled emission tax revenue follow the same pattern as well, making up over one percent of ASPI in Wyoming, W. Virginia, Alaska, Louisiana and N. Dakota.

The details are shown in Table 6, which summarizes the per-capita changes in the components of ASPI in eq. (2). For low values of $\tau_s^{CO_2}$ the resulting revenue stream is sufficiently large that it outweighs both the drop in factor remuneration and the decline in revenue from pre-existing taxes in more than half of the states. In terms of the changes in per-capita factor remuneration, the smallest reductions are found in Mississippi, Arkansas and S. Carolina, while the largest occur in Wyoming, Alaska and W. Virgina. The changes in per-capita revenue from pre-existing indirect business taxes are for the most part smaller by an order of magnitude, with small states such as Washington DC, Connecticut and Vermont seeing significant revenue *increases* and coal-intensive experiencing the largest declines. Even so, it is the latter states which experience the largest windfall gains in recycling of CO_2 tax revenues per-capita, while Rhode Island, New York and California are the states which are worst off in this regard.

To summarize, our results suggest that taxes on CO_2 emissions at or around the safety-valve level proposed in the Bingaman-Domenici Act have a negligible impact on the macroeconomy, generate benefits which are concentrated in the states which produce coal and electricity relatively intensively, and impose costs which are both small in magnitude and widely diffused among large, highly energy-consuming states. This happens because the tax is small enough that its recycled revenues outweigh the declines in factor remuneration and indirect business tax revenues imposed by the costs of emissions abatement which it induces. The driving force behind this phenomenon is the assumption that each state commands the revenue from emission taxes which is are levied within its jurisdiction, which is a consequence of the model's simplified tax structure. More complex patterns of interstate wealth transfers, resulting for example from revenue collection by the federal government followed by recycling to the states according to a formula, generate radically different welfare outcomes. We go on to explore this issue below.

3.3 Cap and trade: the implications of alternative allocation rules [To Be Completed]

Having understood the importance of revenue recycling for the incidence of emission taxes, we now investigate the economic impacts of alternative rules for the allocation of emission rights under an interstate cap-and-trade system. Following Rose and Zhang (2004), we examine four allocation criteria: states' BAU emissions from consumption and production of fossil fuels, population, and equality of economic burdens. The first three of these are easily implemented by expressing each state's BAU emissions as a share of the total across all states, and multiplying the results by the aggregate emission limit ($\overline{Z}$) of 6121 MT which is the dual of the $7/ton tax.

Table 7: Comparing Allocations Based on Emissions from Consumption and Production

	Permit Allocations on a Consumption Basis										Permit Allocations on a Production Basis									
	Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.		Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.	
	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank
AL	146	14	-15	-	4	16	0.14	11	52	12	140	12	-18	17	4	16	0.11	12	42	13
AK	59	36	-15	-	-36	32	0.46	3	192	3	23	35	-67	30	-36	32	-0.51	51	-212	51
AZ	94	23	-15	-	-84	42	-0.02	34	-10	34	12	40	-89	49	-84	42	-0.25	46	-121	48
AR	67	33	-15	-	-20	28	0.19	7	65	8	46	27	-42	20	-20	28	0.03	16	10	17
CA	393	2	-15	-	153	6	-0.10	50	-55	48	586	2	27	9	153	6	-0.03	19	-15	19
CO	84	28	-15	-	34	12	-0.07	46	-41	47	119	18	21	11	34	12	0.03	17	16	16
CT	45	41	-15	-	-28	31	-0.09	48	-60	51	21	36	-60	28	-28	31	-0.17	30	-110	42
DE	16	47	-15	-	-13	22	0.03	25	14	24	3	46	-82	43	-13	22	-0.19	33	-96	38
DC	10	50	-15	-	-8	20	-0.01	32	-4	32	3	48	-74	32	-8	20	-0.14	25	-87	29
FL	268	4	-15	-	-223	51	-0.05	41	-25	41	56	24	-82	44	-223	51	-0.24	44	-117	46
GA	163	12	-15	-	-120	50	0.03	26	12	26	42	30	-78	37	-120	50	-0.20	37	-91	33
HI	19	45	-15	-	-18	26	0.01	30	5	30	3	49	-87	47	-18	26	-0.22	41	-90	32
ID	20	44	-15	-	-17	25	-0.03	36	-12	35	4	45	-81	42	-17	25	-0.22	42	-96	37
IL	226	8	-15	-	28	14	-0.03	37	-16	37	255	8	-4	14	28	14	0.00	18	1	18
IN	250	5	-15	-	-102	46	0.22	6	90	6	129	15	-56	26	-102	46	-0.12	23	-49	23
IA	92	24	-15	-	-76	41	0.12	13	50	13	13	38	-88	48	-76	41	-0.34	50	-140	50
KS	71	32	-15	-	-21	30	0.11	18	44	15	47	26	-43	21	-21	30	-0.04	20	-17	20
KY	182	10	-15	-	257	2	0.10	19	37	19	411	5	92	5	257	2	1.14	4	433	4
LA	228	7	-15	-	216	4	0.68	1	210	2	447	4	67	7	216	4	1.79	3	553	3
ME	23	43	-15	-	-20	29	0.06	21	24	23	5	44	-81	41	-20	29	-0.19	34	-74	28
MD	83	29	-15	-	-40	33	-0.07	45	-41	46	45	29	-53	25	-40	33	-0.16	27	-90	31
MA	80	31	-15	-	-47	37	-0.10	49	-58	50	40	32	-57	27	-47	37	-0.17	29	-102	40
MI	178	11	-15	-	-119	49	0.02	27	10	27	61	23	-71	31	-119	49	-0.18	31	-72	27
MN	96	22	-15	-	-44	36	-0.02	35	-12	36	54	25	-52	24	-44	36	-0.14	24	-71	26
MS	85	27	-15	-	-19	27	0.34	5	103	5	65	21	-35	19	-19	27	0.18	9	54	9
MO	137	17	-15	-	-66	40	0.06	20	25	21	64	22	-60	29	-66	40	-0.16	28	-66	24

Table 7: (Continued)

	Permit Allocations on a Consumption Basis										Permit Allocations on a Production Basis									
	Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.		Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.	
	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank
MT	32	42	-15	-	48	11	0.11	15	41	18	78	20	105	4	48	11	1.09	5	397	5
NE	49	39	-15	-	-41	35	0.16	10	66	7	5	43	-91	51	-41	35	-0.27	48	-114	44
NV	54	38	-15	-	-47	38	0.05	23	28	20	9	41	-86	46	-47	38	-0.23	43	-130	49
NH	19	46	-15	-	-15	24	-0.06	42	-32	43	6	42	-75	34	-15	24	-0.19	35	-110	42
NJ	131	19	-15	-	56	10	-0.06	43	-35	44	195	9	27	8	56	10	0.03	15	18	15
NM	62	34	-15	-	67	9	0.16	8	59	9	127	16	73	6	67	9	0.86	6	307	7
NY	215	9	-15	-	-102	47	-0.10	51	-57	49	132	14	-48	22	-102	47	-0.16	26	-87	30
NC	156	13	-15	-	-118	48	0.02	28	9	28	36	33	-80	39	-118	48	-0.21	40	-94	36
ND	56	37	-15	-	1	17	0.44	4	171	4	46	28	-31	18	1	17	0.13	11	52	10
OH	237	6	-15	-	-95	45	0.06	22	24	22	139	13	-50	23	-95	45	-0.09	22	-36	22
OK	98	21	-15	-	4	15	0.12	12	45	14	101	19	-12	15	4	15	0.14	10	51	12
OR	49	40	-15	-	-40	34	-0.04	39	-20	38	13	39	-78	38	-40	34	-0.20	38	-93	35
PA	278	3	-15	-	106	7	-0.01	33	-6	33	379	6	16	12	106	7	0.11	13	52	11
RI	11	49	-15	-	-10	21	-0.08	47	-36	45	3	47	-76	36	-10	21	-0.20	36	-91	34
SC	87	25	-15	-	-61	39	0.11	17	41	17	24	34	-76	35	-61	39	-0.18	32	-68	25
SD	15	48	-15	-	-14	23	0.02	29	8	29	2	51	-90	50	-14	23	-0.27	49	-118	47
TN	137	18	-15	-	-87	43	0.03	24	13	25	40	31	-75	33	-87	43	-0.25	45	-105	41
TX	688	1	-15	-	159	5	0.11	14	53	10	878	1	9	13	159	5	0.25	8	117	8
UT	62	35	-15	-	95	8	0.11	16	44	15	155	10	112	3	95	8	0.85	7	333	6
VT	8	51	-15	-	-7	19	-0.06	44	-29	42	2	50	-81	40	-7	19	-0.21	39	-96	39
VA	144	15	-15	-	-1	18	-0.04	38	-21	39	142	11	-16	16	-1	18	-0.04	21	-23	21
WA	85	26	-15	-	29	13	-0.05	40	-24	40	121	17	21	10	29	13	0.04	14	19	14
WV	141	16	-15	-	354	1	0.16	9	53	11	467	3	183	2	354	1	3.94	2	1320	2
WI	110	20	-15	-	-92	44	0.01	31	4	31	18	37	-86	45	-92	44	-0.26	47	-115	45
WY	81	30	-15	-	238	3	0.65	2	346	1	305	7	223	1	238	3	6.65	1	3529	1
U.S.	6121		-15		0		0.00		1		6121	0	-15		0		0.00		1	

The allowance allocation under which permits states' welfare losses are equalized must be computed. We employed a secant algorithm, in which at iteration t, the forward projection of state s allowances ($\hat{z}_{s,t+1}$) is determined by the recurrence relation:

$$\hat{z}_{s,t+1} = z_{s,t} - \left[\frac{\Delta_{s,t}}{\Delta_{s,t} - \Delta_{s,t-1}} \right] (z_{s,t} - z_{s,t-1}), \tag{3}$$

where $\Delta_s = PEV_s - \overline{PEV}$ is the deviation of state s psuedo-equivalent variation from the simple average of the welfare losses across all states ($\overline{PEV}$). In general, the sum across states of the projected allocations does not match the economy-wide emission level consistent with the prevailing tax. To enforce consistency, we recast each state's projected allocation as a fraction of total projected emissions, and use the resulting share to apportion the warranted pool of allowances among the states:

$$z_{s,t+1} = \frac{\hat{z}_{s,t+1}}{\sum_s \hat{z}_{s,t+1}} \overline{Z}. \tag{4}$$

The algorithm was initialized using the distribution of emissions under the \$7/ton tax. The CGE model was then solved successively with permit endowments given by the left-hand side of eq. (4). At each iteration, the distribution of welfare losses from the model's solution ($PEV_{s,t}$) provided the gradient information in square braces in eq. (3) necessary to compute the subsequent allocation. The convergence criterion for this procedure is the decline in interstate dispersion of welfare losses, given by the coefficient of variation

$$cv_t = \left(\sum_s \Delta_{s,t}^2 \right) / \overline{PEV}_t.$$

The algorithm converged ($cv \leq 10^{-7}$) in fewer than 20 iterations.

The results for the two emission-based criteria are shown in Table 7, while those for the population and equal welfare loss criteria are given in Table 8.

Table 8: Comparing Allocations Based on Population and Equalizing Welfare Losses

	Permit Allocations on a Population Basis										Permit Allocations on an Equal Welfare Loss Basis									
	Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.		Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.	
	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank
AL	97	23	-44	41	4	16	-0.07	43	-26	42	113	20	-34	39	-23	45	0.00	51	1	47
AK	14	48	-80	50	-36	32	-0.75	48	-313	49	42	39	-39	45	-17	41	0.00	30	1	25
AZ	112	20	2	18	-84	42	0.03	19	15	21	102	25	-8	18	6	16	0.00	16	1	18
AR	58	33	-26	33	-20	28	0.12	3	42	4	42	38	-46	49	-23	46	0.00	33	1	39
CA	738	1	60	3	153	6	0.03	20	16	18	667	1	44	2	234	1	0.00	20	1	6
CO	94	24	-5	22	34	12	-0.05	41	-26	43	111	21	12	9	25	9	0.00	31	1	11
CT	74	29	39	6	-28	31	0.00	34	-2	34	75	28	42	4	26	8	0.00	22	2	1
DE	17	45	-7	24	-13	22	0.05	15	26	14	14	49	-23	28	-2	26	0.00	10	1	6
DC	12	50	8	15	-8	20	0.04	16	28	12	10	51	-11	19	-1	23	0.00	6	2	1
FL	348	4	11	14	-223	51	0.02	24	10	24	327	4	4	12	48	3	0.00	7	1	14
GA	179	10	-6	23	-120	50	0.06	13	25	16	150	13	-21	27	-12	36	0.00	17	1	18
HI	26	42	15	13	-18	26	0.11	5	45	3	19	46	-18	22	-2	25	0.00	2	1	25
ID	28	39	20	9	-17	25	0.08	9	32	10	22	44	-5	16	1	21	0.00	4	1	22
IL	270	5	2	19	28	14	0.02	25	9	26	256	6	-3	15	29	7	0.00	25	1	18
IN	132	14	-55	45	-102	46	-0.11	45	-46	45	172	9	-41	47	-59	49	0.00	50	1	47
IA	64	30	-41	40	-76	41	-0.05	40	-19	40	72	29	-34	38	-17	42	0.00	45	1	44
KS	58	32	-30	34	-21	30	0.03	23	11	23	54	33	-35	41	-14	39	0.00	37	1	32
KY	88	25	-59	46	257	2	-0.33	47	-126	47	161	12	-25	30	8	14	0.00	24	1	32
LA	97	22	-64	47	216	4	0.01	27	4	31	95	26	-65	51	-136	50	0.00	49	0	50
ME	28	40	2	17	-20	29	0.12	2	49	1	19	45	-30	35	-6	30	0.00	18	1	25
MD	115	19	18	12	-40	33	0.00	33	2	32	115	19	18	6	30	6	0.00	19	1	6
MA	138	13	46	5	-47	37	0.01	31	5	29	135	15	43	3	47	4	0.00	15	2	3
MI	216	8	4	16	-119	49	0.09	6	36	7	166	11	-21	25	-15	40	0.00	3	1	25
MN	107	21	-5	21	-44	36	0.01	30	4	30	105	24	-7	17	6	15	0.00	14	1	11
MS	62	31	-38	39	-19	27	0.15	1	46	2	43	37	-57	50	-40	48	0.00	43	1	45
MO	122	17	-24	32	-66	40	0.01	29	5	28	118	18	-27	31	-12	35	0.00	34	1	39

Table 8: (Continued)

	Permit Allocations on a Consumption Basis										Permit Allocations on a Production Basis									
	Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.		Allocation		Abatement		Permit Trade		PEV		Pc. ASPI Chg.	
	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank	MT	Rank	%	Rank	MT	Rank	%	Rank	$	Rank
MT	20	44	-49	44	48	11	-0.16	46	-59	46	27	42	-29	34	-3	28	0.00	38	1	39
NE	37	38	-36	38	-41	35	0.04	18	16	20	34	41	-42	48	-13	38	0.00	23	1	37
NV	44	35	-31	35	-47	38	-0.01	37	-8	37	46	36	-27	32	-9	32	0.00	26	1	11
NH	27	41	18	11	-15	24	0.02	26	10	25	25	43	12	10	5	18	0.00	12	1	5
NJ	183	9	19	10	56	10	0.01	28	8	27	175	8	14	8	35	5	0.00	13	1	4
NM	40	36	-46	43	67	9	-0.08	44	-29	44	47	35	-36	42	-12	37	0.00	46	1	45
NY	412	3	63	2	-102	47	0.03	21	16	18	373	3	48	1	139	2	0.00	21	1	6
NC	175	11	-4	20	-118	48	0.06	12	26	15	146	14	-20	24	-8	31	0.00	39	1	32
ND	14	47	-79	49	1	17	-0.75	49	-293	48	41	40	-38	44	-4	29	0.00	47	1	47
OH	246	7	-11	28	-95	45	0.07	10	30	11	199	7	-28	33	-35	47	0.00	28	1	32
OK	75	27	-35	37	4	15	-0.01	35	-3	35	76	27	-34	37	-21	43	0.00	48	0	51
OR	74	28	30	7	-40	34	0.07	11	33	9	59	31	3	13	6	17	0.00	42	1	25
PA	266	6	-18	30	106	7	-0.03	39	-12	39	290	5	-11	20	17	11	0.00	36	1	22
RI	23	43	69	1	-10	21	0.08	7	40	6	17	47	26	5	4	19	0.00	11	1	14
SC	87	26	-15	29	-61	39	0.11	4	42	5	64	30	-38	43	-21	44	0.00	29	1	32
SD	16	46	-8	25	-14	23	0.04	17	18	17	15	48	-19	23	-1	24	0.00	35	1	22
TN	124	16	-23	31	-87	43	-0.01	36	-3	36	127	17	-21	26	0	22	0.00	41	1	37
TX	454	2	-44	42	159	5	-0.05	42	-25	41	531	2	-34	40	-187	51	0.00	40	1	25
UT	49	34	-33	36	95	8	0.00	32	2	33	48	34	-34	36	-11	34	0.00	44	1	39
VT	13	49	47	4	-7	19	0.08	8	35	8	10	50	14	7	2	20	0.00	5	1	18
VA	154	12	-9	26	-1	18	-0.02	38	-11	38	167	10	-1	14	24	10	0.00	27	1	14
WA	128	15	28	8	29	13	0.05	14	27	13	106	23	6	11	14	12	0.00	9	1	14
WV	39	37	-76	48	354	1	-1.01	50	-340	50	127	16	-23	29	14	13	0.00	8	1	39
WI	117	18	-10	27	-92	44	0.03	22	13	22	108	22	-17	21	-3	27	0.00	32	1	25
WY	11	51	-89	51	238	3	-1.21	51	-644	51	56	32	-40	46	-10	33	0.00	1	1	6
U.S.	6121		-15		0		0.00		1		6121		-15		0		0.00		1	

4 Conclusions [To Be Completed]

A Algebraic Description of the Model

Variables

$p_{j,s}$	producer price index in industry j and state s
P_i	Armington commodity i price index, $i = \{e$ (energy), m (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_s^U	Price of utility good in state s (= 1 in Washington DC, numeraire)
z_s	CO_2 emission limit in state s
$\tau_s^{CO_2}$	CO_2 tax (price dual of emission limit) in state s
$y_{j,s}$	Activity level for industry j in state s
Y_i	Activity level for Armington commodity i
A_s^L	Activity level for aggregate labor demand in state s
A^K	Activity level for 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
$\theta_{VA,j,s}$	Production coefficient on value added in industry j and state s
$\theta_{L,j,s}$	Labor share of value added in industry j and state s
$\theta_{K,j,s}$	Capital share of 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
$\overline{\tau}_{j,s}$	Industry j/state s pre-existing indirect business taxes
ϕ_e	Energy commodity e stoichiometric CO_2 coefficient

Substitution elasticities

$\sigma^{Y}_{j,s}$	Elasticity of substitution in production in industry j and state s
σ^{A}_{j}	Industry j interstate Armington elasticity of substitution
σ^{C}_{s}	State s final use expenditure elasticity of substitution
σ^{KT}	Elasticity of transformation of aggregate capital into sector-specific capital
σ^{LA}_{s}	Elasticity of aggregation of labor across states
σ^{LT}_{s}	Elasticity of transformation of total state labor into sector-specific labor

Zero Profit Conditions

(A) $N \times S$ conditions defining zero profit in the production of commodities within states, dual to the $N \times S$ activity levels of industries within states:

$$p_{j,s} = (1+\overline{\tau}_{j,s}) \left[\sum_e \theta_{e,j,s}^{\sigma_{j,s}^Y} (P_e + \phi_e \tau_s^{\mathrm{CO_2}})^{1-\sigma_{j,s}^Y} + \sum_m \theta_{m,j,s}^{\sigma_{j,s}^Y} P_m^{1-\sigma_{j,s}^Y} + \theta_{VA,j,s}^{\sigma_{j,s}^Y} \left(w_{j,s}^{\theta_{L,j,s}} r_{j,s}^{\theta_{K,j,s}} \right)^{1-\sigma_{j,s}^Y} \right]^{1/(1-\sigma_{j,s}^Y)} \quad \perp \quad y_{j,s} \qquad \text{(ZP1)}$$

(B) N conditions defining zero profit in interstate trade in commodities, dual to the N Armington aggregate commodity supply activity levels:

$$P_j = \left(\sum_s \mu_{j,s}^{\sigma_j^A} p_{j,s}^{1-\sigma_j^A} \right)^{1/(1-\sigma_j^A)} \quad \perp \quad Y_j \qquad \text{(ZP2)}$$

(C) S conditions defining state-level expenditure on final uses, dual to the S state income levels:

$$p_s^U = \left[\sum_e \alpha_{e,s}^{\sigma_s^C} (P_e + \phi_e \tau_s^{\mathrm{CO_2}})^{1-\sigma_s^C} + \sum_m \alpha_{m,s}^{\sigma_s^C} P_m^{1-\sigma_s^C} \right]^{1/(1-\sigma_s^C)} \quad \perp \quad U_s \qquad \text{(ZP3)}$$

(D) S conditions defining zero profit in the aggregation of states' labor and the transformation of the resulting supply into industry-specific labor, dual to the S state-level labor supply activity levels:

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

(E) A single condition defining zero profit in the transformation of states' capital endowments into industry-specific capital, dual to the activity level of aggregate capital supply:

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

Market Clearance Conditions

(A) N conditions defining aggregate supply-demand balance for commodities, dual to the N aggregate commodity prices:

$$Y_e = \sum_s \left[\sum_j \theta_{e,j,s}^{\sigma_{j,s}^Y} \left(\frac{p_{j,s}}{P_e + \phi_e \tau_s^{\mathrm{CO_2}}} \right)^{\sigma_{j,s}^Y} y_{j,s} + \alpha_{e,s}^{\sigma_s^C} \left(\frac{p_s^U}{P_e + \phi_e \tau_s^{\mathrm{CO_2}}} \right)^{\sigma_s^C} U_s \right] \quad \perp \quad P_e \qquad \text{(MC1a)}$$

$$Y_m = \sum_s \left[\sum_j \theta_{e,j,s}^{\sigma_{j,s}^Y} \left(\frac{p_{j,s}}{P_m} \right)^{\sigma_{j,s}^Y} y_{j,s} + \alpha_{m,s}^{\sigma_s^C} \left(\frac{p_s^U}{P_m} \right)^{\sigma_s^C} U_s \right] \quad \perp \quad P_m \qquad \text{(MC1b)}$$

(B) $N \times S$ conditions defining supply-demand balance for industries' outputs, dual to the $N \times S$ producer prices:

$$y_{j,s} = \mu_{j,s}^{\sigma_j^A} \left(\frac{P_j}{p_{j,s}} \right)^{\sigma_j^A} Y_j \quad \perp \quad p_{j,s} \qquad \text{(MC2)}$$

(C) S conditions defining aggregate supply-demand balance for labor across states, dual to the S average state wage levels:

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

(D) $N \times S$ conditions defining the supply-demand balance for industry-specific labor within each state, dual to the $N \times S$ industry-specific wage levels:

$$\gamma_{j,s}^{\sigma_j^{LT}} \left(\frac{W_s}{w_{j,s}} \right)^{\sigma_j^{LT}} A_s^L = \theta_{L,j,s} \theta_{VA,j,s}^{\sigma_{j,s}^Y} \left(\frac{p_{j,s}}{w_{j,s}^{\theta_{L,j,s}} r_{j,s}^{\theta_{K,j,s}}} \right)^{\sigma_{j,s}^Y} \frac{y_{j,s}}{w_{j,s}} \quad \perp \quad w_{j,s} \qquad \text{(MC4)}$$

(E) A single condition defining the supply-demand balance for aggregate capital, dual the aggregate rental rate:

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

(F) $N \times S$ conditions defining the supply-demand balance for industry-specific capital, dual to the $N \times S$ industry-specific rental rates:

$$\kappa_{j,s}^{\sigma^{KT}} \left(\frac{R}{r_{j,s}} \right)^{\sigma^{KT}} A^K = \theta_{K,j,s} \theta_{VA,j,s}^{\sigma_{j,s}^Y} \left(\frac{p_{j,s}}{w_{j,s}^{\theta_{L,j,s}} r_{j,s}^{\theta_{K,j,s}}} \right)^{\sigma_{j,s}^Y} \frac{y_{j,s}}{r_{j,s}} \quad \perp \quad r_{j,s} \qquad \text{(MC6)}$$

Income Balance Conditions

$S-1$ equations defining state income as the sum of factor returns, recycled indirect business tax revenue and recycled emission tax revenue, dual to the $S-1$ prices of "utility goods":

$$U_s = W_s L_s + R K_s + \overline{\tau}_{j,s} p_{j,s} y_{j,s} + \tau_s^{CO_2} \mathscr{E}_s \quad \perp \quad p_s^U . \qquad \text{(IB)}$$

p_s^U is analogous to the vector of state-level consumer price indices. p_s^U for Washington DC is taken as the numeraire price in the model: its value is fixed at unity, and the corresponding income definition is dropped. State-level emissions are given by the total use of fossil fuels, weighted by the corresponding emission factors:

$$\mathscr{E}_s = \sum_e \phi_e \left[\sum_j \theta_{e,j,s}^{\sigma_{j,s}^Y} \left(\frac{p_{j,s}}{P_e + \phi_e \tau_s^{CO_2}} \right)^{\sigma_{j,s}^Y} y_{j,s} + \alpha_{e,s}^{\sigma_s^C} \left(\frac{p_s^U}{P_e + \phi_e \tau_s^{CO_2}} \right)^{\sigma_s^C} U_s \right]$$

Emission constraints

In the case of autarkic compliance, S equations defining quantitative limits on emissions, dual to the S shadow prices on CO_2. With emission trading, a single aggregate limit on all states' emissions, dual to the market-clearing price of CO_2:

$$\mathscr{E}_s \leq z_s \quad \perp \quad \tau_s^{CO_2} \tag{ELa}$$

$$\sum_s \mathscr{E}_s \leq Z \quad \perp \quad \tau^{CO_2} \tag{ELb}$$

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), the $S - 1$ income balance conditions (IB) and S (or single) emission limits (EL). Given a vector of state emission limits, the result is a square system of $(4(N \times S) + 2N + 5S)$ nonlinear equations, $\Im(\mathbf{b})$, in $(4(N \times S) + 2N + 5S)$ unknowns, $\mathbf{b} = \{p_{j,s}, P_i, W_s, w_{j,s}, R, r_{j,s}, P_s^U, \tau_s^{CO_2}, y_{j,s}, Y_i, A_s^L, A^K, U_s\}$.

References

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

Babiker, M., Reilly, J. M., Jacoby, H. D., 2000. The kyoto protocol and developing countries. Energy Policy 28, 525–536.

Balistreri, E. J., Rutherford, T. F., 2004. Assessing the state-level burden of carbon emissions abatement. Mimeographed paper, Colorado School of Mines, Golden, CO.

Blasing, T. J., Broniak, C. T., Marland, G., 2004. Estimates of annual fossil-fuel CO_2 emitted for each state in the U.S.A. and the District of Columbia for each year from 1960 through 2001. In: Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.

Dirkse, S. P., Ferris, M. C., 1995. The PATH solver: A non-monotone stabilization scheme for mixed complementarity problems. Optimization Methods and Software 5, 123–156.

DOE/EIA, 2003a. Annual energy outlook 2006 with projections to 2030. Tech. Rep. DOE/EIA-0383(2006).

DOE/EIA, 2003b. State energy data 2000: Consumption, technical notes. Tech. rep.

DOE/EIA, 2003c. State energy data report. Tech. rep.

Eckaus, R. S., Ellerman, A. D., Jacoby, H. D., Prinn, R. G., Reiner, D. M., Yang, Z., 1997. CO_2 emissions limits: Economic adjustments and the distribution of burdens. Energy Journal 18, 31–58.

Jackson, R. W., 1998. Regionalizing national commodity-by-industry accounts. Economic Systems Research 10, 223–238.

Li, P.-C., Rose, A. Z., 1995. Global warming policy and the Pennsylvania economy: A computable general equilibrium analysis. Economic Systems Research 7, 151–171.

Mathiesen, L., 1985a. Computation of economic equilibrium by a sequence of linear complementarity programs. Mathematical Programming Study 23, 144–162.

Mathiesen, L., 1985b. Computational experience in solving equilibrium models by a sequence of linear complementarity problems. Operations Research (33), 1225–1250.

McLure, C. E., 1971. The theory of tax incidence with imperfect factor mobility 30, 432–453.

Partridge, M. D., Rickman, D. S., 1998. Regional computable general equilibrium modeling: A survey and critical appraisal. International Regional Science Review 3, 205–250.

Petchey, J. D., Levtchenkova, S., 2003. Welfare effects of national taxes in an economy with regions. The Economic Record 79, 218–228.

Rose, A. Z., Stevens, B. K., Edmonds, J. A., Wise, M., 1998. International equity and differentiation in global warming policy. Environmental and Resource Economics 12, 25–51.

Rose, A. Z., Zhang, Z. X., 2004. Interregional burden-sharing of greenhouse gas mitigation in the united states. Mitigation and Adaptation Strategies for Global Change 9, 477–500.

Ross, M. T., Beach, R. H., Murray, B. C., 2004. Distributional implications of regional climate change policies in the U.S.: A general equilibrium assessment. Paper presented at the AERE summer workshop on distributional effects of environmental policy, June 14-15, Estes Park, CO.

Rutherford, T. F., 1987. Implementational issues and computational performance solving applied general equilibrium models with SLCP. Cowles Foundation Discussion Paper No. 837, Yale University.

Scarf, H., 1973. The Computation of Economic Equilibria. Yale University Press, New Haven, CT.

Sue Wing, I., 2004. Computable general equilibrium models and their use in economy-wide policy analysis. Technical Note No. 6, MIT Joint Program on the Science & Policy of Global Change.

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 US CO_2 emissions. Energy Policy In press.

Sue Wing, I., Anderson, W. P., forthcoming. Modeling small area economic change in conjunction with a multiregional cge model. In: Cooper, R. J., Donaghy, K. P., Hewings, G. J. (Eds.), Globalization and Regional Economic Modeling. Springer-Verlag.