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The Regional Impacts of U.S. Climate Change Policy

A General Equilibrium Analysis

Ian Sue Wing⋆

[1] Dept. of Geography & Environment, Boston University, Address: Rm. 461, 675 Commonwealth Ave., Boston, MA 02215. Email: isw@bu.edu Ph.: (617) 353-4751. Fax: (617) 353-5986.

[2] Joint Program on the Science & Policy of Global Change, MIT

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Abstract This paper investigates the impacts at the state and regional levels of policies to limit U.S. carbon dioxide (CO_2) emissions. It constructs an interregional computable general equilibrium model which divides the U.S. economy into ten industries and 50 states, and simulates the effects of economy-wide CO_2 emission taxes. The results elucidate the sources and consequences of the incidence of abatement costs, as well as the implications of alternative rules for recycling emission tax revenue for the interregional distribution of the economic burden of national climate policies.

Keywords: Computable general equilibrium models, Carbon tax, Emission limits, Regional science, Interstate distribution

JEL Codes: C68, H23, H71, Q52, R13

1 Introduction

A number of recent U.S. climate change policy proposals seek to impose limits on the economy's emissions of greenhouse gases (GHGs). For example, legislation such as the McCain-Lieberman and Bingaman-Domenici bills have sought

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to introduce an economy-wide emission target,[1] while at the state or regional levels similar instruments are the centerpiece of California's recently-enacted climate legislation and the Regional Greenhouse Gas Initiative (RGGI) in New England and Mid-Atlantic states.[2] A key feature of all of these policies is that their economic costs are likely to distributed unevenly among states and regions, but the relevant spatial patterns and their precursors have yet to be systematically characterized.[3] The present study addresses this need by constructing a computable general equilibrium (CGE) model of the U.S. economy, which simulates the incidence of economy-wide taxes on carbon dioxide (CO_2) at the state level.

An understanding of the geographic incidence of climate change mitigation policies is crucial to their design and implementation in federal political systems. Federal lawmakers face strong incentives to avoid the costs of such regulations falling on their own constituents, which makes concentrated political opposition likely to arise wherever deadweight economic losses are geographically localized. The upshot is a classic collective action problem. This issue has long been a feature of the international negotiations on climate change, and was a major factor in the U.S. withdrawal from the Kyoto Protocol.[4] The large literature analyzing this policy (e.g. Weyant, 1999) has generated several insights which are relevant to the question of incidence at the sub-national level. It is instructive to consider a few of them:

1. Declining factor remuneration is the primary channel through which climate policy affects welfare in abating regions. Not only do the the returns to labor and capital constitute the majority of household income, the imperfect mobility of these factors across regions and among industries—especially in the short run—causes the incidence of a carbon tax to fall most heavily

[1] The McCain-Lieberman Climate Stewardship and Innovation Act of 2007 would set caps on GHG emissions at year-2004 levels by 2012 and 1990 levels by 2020. The Bingaman-Domenici Climate and Economy Insurance Act (an amendment to H.R.6, the Energy Policy Act of 2005) seeks to set 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 whereby the government would issue emission permits to keep the marginal cost of abatement below \$7/ton CO_2.

[2] California's Global Warming Solutions Act of 2006 (AB32) would cap the state's emissions at a level based on 1990 emissions by the year 2020, while RGGI seeks to stabilize CO_2 emissions from electricity generation in seven states (Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York and Vermont) at year-2005 levels over the period 2009-2015.

[3] Petchey and Levtchenkova (2003) report a general dearth of analysis of the regional incidence of national taxes. With respect to climate change, prior research has tended to focus on the effects of Kyoto-type policies. 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 unilateral GHG abatement by different regions. Rose and Zhang (2004) estimate how the distribution of abatement costs across ten U.S. regions changes with different rules for the allocation of tradable emission allowances under a Kyoto-style aggregate limit.

[4] See, e.g., Jacoby and Reiner (2001).

upon them (McLure, 1971).[5] An emission limit increases the costs of production in polluting firms, reducing their demands for labor and capital, and this depresses income and welfare as wages and rental rates fall to clear factor markets. The present study estimates the effect of an aggregate emission limit on both the magnitude of the aggregate deadweight loss and its distribution across the 50 U.S. states and the District of Columbia. As with Kyoto, the state-level impacts of a domestic policy depend on the geographic distribution of key industries—in particular the share of states' gross product in sectors which produce fossil fuels or use them intensively as inputs.

2. Substitution effects play an important role in moderating welfare losses (Jorgenson et al., 2000). The ease with which producers can switch from carbon-rich fuels such as coal to low-carbon fuels such as natural gas, or replace fossil fuels with non-energy inputs, determines the abundance of cheap abatement opportunities which can mitigate the rise in their production costs. Symmetrically, as increases in the cost of producing fossil fuels and their derivative commodities are passed on to downstream users, consumers' ability to shift their expenditure to relatively lower-priced substitutes moderates the erosion of their consumption in real terms. There is concern among policy makers that the pervasiveness of energy use and the lack of substitutes for fossil fuels will lead to emission limits having unacceptably high economic costs. However, the results suggest that the policies currently under consideration do not unduly burden the economy, and may actually *increase* welfare in several states.
3. A key influence on the distribution of policy costs is terms-of-trade improvements in the regions which export GHG-intensive goods (Babiker et al., 2000, Böhringer and Rutherford, 2002). The latter are precipitated by increases in the prices of these commodities as emission limits bind. The fewer options consumers have to substitute away from fossil fuels and their derivative commodities, the smaller the reductions in the demand for them, and the larger the increases in their prices. The less elastic the demand in importing regions, the larger the benefit to exporters, and the larger the loss to importers, whose primary abatement burdens are exacerbated by higher import costs. In the present context this effect arises from the scale and homogeneity of interstate commodity markets, as well as imperfect factor mobility's curtailment of the expansion of import-competing industries in states which import large quantities of domestically-produced energy (cf. Balistreri and Rutherford, 2004).
4. In the second-best world of an initially tariff-ridden economy, the contractionary effect of GHG taxes on production reduces the revenue from pre-existing business and factor taxes, lowering the revenue ultimately returned to households as income, while the lump-sum return of GHG tax revenue

[5] McLure's result also applies to fossil fuel extraction and processing industries, which are often tied to geographically fixed resource deposits. The cost of an emission limit will then be borne disproportionately by regions where such resources naturally occur. While this issue is of particular concern for states which are specialized in the production of fossil fuels, resource fixed factors are not explicitly dealt with in this analysis.

to households increases their real income. While the sign of the net effect of these two influences is uncertain in theory, previous economic simulations—either of the single-country (e.g., Goulder et al., 1997) or multi-region (e.g., Babiker et al., 2003) variety—generally find it to be negative. However, these studies do not capture an essential element of federal fiscal systems, namely the degree to which sub-national jurisdictions are allowed to recycle locally-raised tax revenue within their own borders, as opposed to being required to treat these funds as federal revenues to disbursed among all jurisdictions as federal spending.[6] The present study examines the implications of both schemes for the return of emission tax revenues to consumers, and finds that although their effects are almost identical at the level of the aggregate economy, their impacts on the inter-regional distribution of welfare losses are markedly different.

CGE models are a standard tool for estimating the signs and magnitudes of these effects, and for analyzing their joint consequences in a consistent manner. The vast majority of general equilibrium analyses of climate policies focus on the aggregate economy as the unit of analysis. Inter-regional CGE (ICGE) models of the U.S. economy have been developed, but these typically resolve either coarse areal detail such as the census regions, or an individual state.[7] The contribution of the present study is to develop an ICGE model which, to the author's knowledge, is the first to simultaneously resolve *all* states, and to simulate both the interstate system of taxes and transfers as well as the general equilibrium effects of abatement on the distribution of income.

From a political economy standpoint, a natural prior is that the costs of abatement are concentrated in a small number of states which produce fossil-fuels intensively, and therefore have an incentive to obstruct the passage of legislation to limit aggregate emissions. The simulation results illustrate that although this simplistic view is consistent with the distribution of states' primary abatement burdens, it is the scheme by which the revenue from emission taxes is recycled that is responsible for rich and complex geographic patterns of welfare change.

The rest 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 simula-

[6] There is a literature which examines the impacts of climate change mitigation policies on the distribution of income in the economy (see, e.g., the summary in Oladosu and Rose, In Press), but its focus is aspatial.

[7] A large, mostly older literature employs interregional and single-state CGE models in regional economic analysis (see, e.g., the survey by Partridge and Rickman, 1998). I 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.

tion 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 over a broad range, and explores the redistributive consequences of different rules for allocating tradable emission permits among the states. Section 4 offers a summary and concluding remarks.

2 Model, Data and Calibration

2.1 Model structure

The ICGE model is a static spatial price equilibrium simulation of the U.S. economy based on the prototype outlined in Sue Wing and Anderson (forthcoming). Its structure 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 I 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. To keep things simple the analysis focuses only on CO_2, and does not consider emissions of other GHGs such as methane.

In each industry and state, firms produce output ($y_{j,s}$) from capital ($k_{j,s}$), labor ($l_{j,s}$) 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 constant elasticity of substitution (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 production.

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 generated an Armington CES composite of 51 individual state varieties. The result is that 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 producer prices. Market clearance is given by:

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

where the symbol "$\perp$" indicates complementary slackness between the primal condition on the left and the dual variable on the right, which can be thought of as a Lagrange multiplier.

To capture the imperfect mobility of factors across states and among industries, I employ the transformation functions shown schematically in Figure 1(b).[8] Imperfect factor mobility creates a divergence at the state level between the total demand for labor and capital and the corresponding endowments (L_s and K_s, respectively), with the result that $L_s \neq \sum_j l_{j,s}$ and $K_s \neq \sum_j k_{j,s}$. I 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 geographic 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 ($A^L_d = \sum_j l_{j,d}$), 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.

The model does not explicitly represent either the federal or state governments. A simplified structure is employed in which each representative agent levies state taxes (indicated by the superscipt "S") and federal taxes (indicated by the superscript "F") on the production ($\overline{\tau}^{Y,\mathrm{S}}_{j,s}$ and $\overline{\tau}^{Y,\mathrm{F}}_{j,s}$), payments to capital ($\overline{\tau}^{K,\mathrm{S}}_{j,s}$ and $\overline{\tau}^{K,\mathrm{F}}_{j,s}$) and payments to labor ($\overline{\tau}^{L,\mathrm{S}}_{j,s}$ and $\overline{\tau}^{L,\mathrm{F}}_{j,s}$), of the industries within her jurisdiction. These six tax rates are parameters which capture the effect of pre-existing distortions in the database used to calibrate the model, and define the benchmark sources of recycled revenue to which supplementary emissions taxes will be added. Using $t \in \{\mathrm{S},\mathrm{F}\}$ to denote tax collections by state and federal

[8] Cf. multi-country CGE models, in which the standard assumption is that primary factors are completely immobile among countries, but completely mobile among sectors.

governments, these components are:

Revenue from pre-existing labor taxes: $$LTR_s^t = \sum_j \overline{\tau}_{j,s}^{L,t} w_{j,s} l_{j,s}, \quad (1a)$$

Revenue from pre-existing capital taxes: $$KTR_s^t = \sum_j \overline{\tau}_{j,s}^{K,t} r_{j,s} k_{j,s}, \quad (1b)$$

Revenue from pre-existing production taxes: $$YTR_s^t = \sum_j \overline{\tau}_{j,s}^{Y,t} p_{j,s} y_{j,s}. \quad (1c)$$

Revenue collected from state taxes is recycled in situ as a lump-sum supplement to each jurisdiction's income, while the revenue collected from federal taxes is subject to an outward transfer to the (notional) federal government. The latter is offset by a countervailing inward income transfer as a result of federal spending. Each state's budgetary position is modeled by specifying the net of the two transfers as a component of income. Income balance is enforced via a constraint mandating that the sum across all states of the net transfers is zero.

The key feature of the model is that emission taxes interact with this system of pre-existing taxes and transfers. Taxes on CO_2 emissions, $\tau_s^{CO_2}$, are synonymous with both the price of CO_2 and the marginal cost of its abatement in each state, and are modeled as commodity-specific markups on the prices of fossil fuels. The size of the markup is proportional to each fuel's carbon content, which is represented by constant emission factors (ϕ_e) that translate units of each fossil fuel into units of CO_2.[9] The gross-of-tax consumer price of fossil fuels is then given by $P_e + \phi_e \tau_s^{CO_2}$. In a general equilibrium setting, carbon taxes may be thought of as the price duals of quantitative limits on states' emissions (z_s), and in turn their total use (*not* production) of fossil fuels:

$$\mathscr{E}_s \le z_s \quad \perp \quad \tau_s^{CO_2}, \quad (2)$$

where $\mathscr{E}_s = \sum_e \varepsilon_{e,s}$ denotes total emissions and $\varepsilon_{e,s} = \phi_e \left(c_{e,s} + \sum_j x_{e,j,s} \right)$ is the CO_2 emissions associated with the each category of fuel. For the sake of transparency, the analysis abstracts from the institutional details of policies such as McCain-Lieberman or Bingaman-Domenici bills, and considers only the effects of an economy-wide tax ($\overline{\tau}^{CO_2}$), by setting $\tau_s^{CO_2} = \overline{\tau}^{CO_2}$.[10]

[9] The coefficients ϕ_e were calculated to be consistent with aggregate economic and emissions data, by dividing the benchmark quantity of total emissions associated with fuel e ($\sum_s \overline{\varepsilon}_{e,s}$) by the benchmark economic quantity of fuel demanded, $\sum_s \left(\sum_j \overline{x}_{e,j,s} + \overline{c}_{e,s} \right)$.

[10] Both proposals envision an aggregate cap on GHGs in conjunction with a system of tradable emission permits. Such instruments may be simulated by solving the model for the unique market-clearing price of emission allowances which is consistent with a prescribed economy-wide emission limit, $\overline{Z} = \sum_s \overline{z}_s$:

$$\sum_s \mathscr{E}_s \le \overline{Z} \quad \perp \quad \widetilde{\tau}^{CO_2}.$$

States choose their levels of emissions optimally by setting their marginal cost of abatement equal to the permit price, $\tau_s^{CO_2} = \widetilde{\tau}^{CO_2}$. Unlike the formulation in the text, $\widetilde{\tau}^{CO_2}$ is an endogenous variable whose value is determined by the level of the aggregate cap, $\overline{Z}$.

Eq. (2) implies that by putting a price on CO_2 while permitting residual emissions, climate policy generates a stream of rents which must be allocated somewhere in the economy. The welfare consequences may be seen by considering 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:

$$\mathrm{GSP}_s = \left(\sum_j w_{j,s} l_{j,s} + \sum_j r_{j,s} k_{j,s}\right) \tag{3}$$

$$\mathrm{ASPI}_s = (W_s L_s + RK_s) + TR_s^{\mathrm{S}} + FE_s + NFA_s. \tag{4}$$

The variable FE_s denotes expenditures by the federal government in state s, which indicates each state's inward transfer of recycled federal funds, TR_s^{S} denotes state tax revenue raised in s which is recycled as income, $NFA_s = \sum_i P_i \overline{n}_{i,s}$ indicates each state's net foreign asset position, and the terms in parentheses in both equations denote factor remuneration.[11]

The model is closed by imposing budgetary balance at the federal level:

$$\sum_s FE_s = \sum_s TR_s^{\mathrm{F}}, \tag{5}$$

where TR_s^{F} indicates federal tax revenue raised in s. The closure rule turns on the assumption that the pattern of federal spending is invariant to climate policy, so that the ratio $\omega_s = FE_s / \sum_s FE_s$ is the same with the CO_2 tax shock as in the no-policy scenario. The value of ω_s is set equal to the state share of federal government spending in the benchmark dataset used to calibrate the model. The tax receipts in eq. (4) are derived from the three sources in eq. (1), plus the revenue from taxes on CO_2 emissions, $CTR_s = \tau_s^{\mathrm{CO_2}} \mathscr{E}_s$. The decision to recycle emission tax revenues at the state or federal levels becomes important here, as the following condition illustrates:

$$TR_s^t = LTR_s^t + KTR_s^t + YTR_s^t + \begin{cases} CTR_s & \text{Revenue recycling to tax agent } t \\ 0 & \text{Otherwise} \end{cases} \tag{6}$$

Substituting this expression into eq. (4) we see that with recycling at the state level CTR_s becomes a component of TR_s^{F}, so that emission tax revenue raised within a particular state redounds only to that state's representative agent, with a direct positive impact on ASPI. Conversely, with recycling at the federal level CTR_s is subject to an *outward* transfer to the federal tax authority as a component of TR_s^{F}, but by eq. (5), the concomitant increase in aggregate federal spending results in a broader distribution of revenue back to *all* of the states.

The geographic pattern of welfare impacts depends on states' individual allocations of allowances under the cap, $\overline{z}_s$, which is the key decision variable for policy makers.

[11] In general, labor and capital mobility are responsible for a divergence between factor income in (4) and GSP in (3). This is especially important in small states such as Hawaii, Rhode Island and Washington DC.

ASPI, deflated by the price of aggregate consumption in each state (P_s^U), is the measure of each state's economic welfare, the change in which I call pseudo-equivalent variation (PEV).[12] The discussion above makes clear that the change in welfare due to an emission tax depends on three factors: the adverse direct effect of the tax on the returns to labor and capital, the beneficial indirect effect of recycled revenues from carbon taxes or auctioned permits, and the ambiguous impact of emission constraints on revenue from pre-existing taxes. The advantage of the model's structure is that it makes transparent the nature of the interactions among these components of income.

2.2 Data development

Official data on state social accounting matrices (SAMs) are not published by the Bureau of Economic Analysis (BEA). I therefore employed available state-level data from BEA on personal income and value added, energy consumption data from DOE/EIA (2003b,a) 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.[13] The result is a consistent set of interregional social accounts, which form the calibration point for the model outlined above. Below I provide a brief description of the method, which builds on Sue Wing and Anderson (forthcoming):

2.2.1 Disaggrgegating the components of value added at the state level The starting point for the interregional database is the aggregate SAM for the U.S. economy in the year 2000 described in Sue Wing (2005). The first task was to disaggregate the factor demand account, allocating the labor and capital returns and production tax revenues of each industry the national SAM to the states. This was done separately for each 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.

2.2.2 Estimating state and federal taxes on production and factor income The second task was to disaggregate industries' payments of state and federal taxes

[12] Equivalent variation is a *consumption*-based measure, but data constraints prevent me from resolving the components of final use at the state level. I therefore attribute the income spent on *all* final uses to households' welfare.

[13] The full set of state-level SAMs is estimated by IMPLAN, but the cost of these data is prohibitive. Similar datasets have been constructed from official statistics by Research Triangle Institute (Ross, 2005) and Randall W. Jackson and co-authors (Jackson, 1998, Jackson et al., 2004), but these are either proprietary or not in a form which can be used for the present analysis. Investigating the use of these data is a priority for future research.

as components of the benchmark production tax revenues and returns to labor and capital in each state. The primary data sources were BEA's annual state income estimates, IRS (2001),[14] IRS Individual Tax Statistics (ITS),[15] and the Census Bureau's State Government Tax Collections and Consolidated Federal Funds Report data files for FY2000 (STC 2000 and CFFR 2000, repectively). State sales taxes are not represented in the model, as these tend to be levied on consumption activities which are not resolved in the benchmark dataset.

The tax burdens tabulated by BEA's regional accounts represent the sum of state and federal component of taxes on production and imports (TOPI). To disaggregate federal TOPI, I used data on federal excise tax collections by state. These payments were allocated among sectors in proportion to the inter-industry distribution of TOPI among states' GSP, with state TOPI being computed as the residual.

STC (2000) and IRS (2001) were the source for data on state and federal individual income tax payments. ITS data were used to estimate the shares of states' taxable income attributable to labor and capital remuneration, and these proportions were used to disaggregate each state's income tax payments into state and federal taxes on labor and capital. The latter were then used to estimate state and federal tax burdens as components of the payments to factors made by the various sectors in each state. This was done by allocating states' total tax payments according to the distribution of of labor and capital among industries.

STC (2000) and IRS (2001) yielded data on states' payments of state and federal corporation, estate and gift taxes. These totals were allocated among sectors in proportion to the inter-industry distribution of sectors' capital returns in each state.

2.2.3 Estimating state-level intermediate transactions The third task was to allocate intermediate input among the states. To do this, I employed the key simplifying assumption that the production technology in a given industry was the same for all states with respect of intermediate commodity uses. For each industry (column) of the national I-O table, I expressed the share of each intermediate commodity use (row) as a share of value added. I 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.

2.2.4 Estimating state energy use and CO_2 emissions by fuel 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 (2003b,a), by using these data to allocate states' shares of each fuel in each of the corresponding industries.

[14] Table 6: Internal Revenue Gross Collections by State, FY2000.
[15] Expanded unpublished data on state income for FY2000.

The need for accurate CO_2 accounting also constrained my estimates of final use by commodity. I 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 foregoing estimates of gross intermediate use of each fuel 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.

I used a very simple procedure to disaggregate final uses of non-fossil energy commodities and non-energy goods. I first estimated state's gross income by dividing total final demand in the aggregate SAM according to states' share of aggregate final expenditure in 2000. I then subtracted states' gross final expenditure on fossil fuels estimated in the previous step, to yield estimates of gross non-fuel expenditures. The 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.

2.2.5 Estimating 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 consequence of interstate labor and capital mobility.[16] The only data available on interstate factor movements were the 2000 Census county-to-county worker flow files, which I aggregated up to the state level. The resulting matrix of origin-destination flows was used in conjunction with data from the BEA regional accounts on states' employment and average wages to compute the share of total labor compensation ($\lambda_{o,d}$) in each destination state (d) paid to commuters from other origin states (o). I then estimated the labor endowment of each state s as its own industries' demand for labor minus its labor imports from other origins plus its labor exports to other destinations:

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

The last step was then to calculate 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 2, aggregated to the level of census regions. Their major limitations are the absence of data on state-to-state commodity flows (which necessitated the use of an interstate Armington price structure as a workaround), and the lack of resolution of consumption as a component of final demand. Remedying these shortcomings is a priority for future research.

[16] 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 Numerical 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, whereby 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 is derived by 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). The details are given in an appendix. 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 key exogenous parameters employed in the calibration procedure are the elasticities of substitution and transformation, which are drawn from a variety of sources.[17] The calibrated model replicates the economic conditions in both the national SAM and the regional accounts in the benchmark year, and closely matches the vector of state-level emissions in Blasing et al. (2004).

A common feature of the proposals outlined in the introduction is their entry into force in the post-2010 timeframe. To be policy-relevant the business-as-usual (BAU) scenario of the model was chosen to simulate economic conditions in 2015. This baseline was constructed by scaling the economic flows in the year-2000 benchmark to match projections of historical trends in GSP and the CO_2 intensity of output. It was assumed that each state's GSP would continue to expand at its average annual rate of growth over the period 1994-2004, and the endowments of labor and capital were scaled up to match these trends. States' emissions intensities were also projected to continue evolving at the average annual rates of change over the period 1994-2001, and the coefficients on fossil fuel inputs in industries' cost functions and state agents' expenditure functions were scaled to be consistent with these trends. To estimate per-capita

[17] Balistreri et al. (2003) provide evidence for a unitary elasticity of substitution between capital and labor within industries. The interfuel, Armington and household elasticities of substitution (σ^E, σ^A and σ^C, respectively) are taken from Bovenberg and Goulder (1996). Within each industry, production at the national level is likely to exhibit a greater degree of reversiblity relative to that at finer spatial scales, because price-induced adjustments in input and output quantities will be spread over a smaller number of firms in the latter case. By this logic, input substitutability at the state level should be relatively inelastic, a phenomenon which is captured by the assumption of a fixed-coefficient (Leontief) relationship among non-fuel intermediate goods, and between the corpus of these inputs and the energy and value-added composites. No empirical estimates could be found for the elasticities governing the fungibility of labor and capital across states and industries. I assumed inelastic values for these parameters, to reflect interindustry differences and the friction of distance ($\sigma^{LA} = \sigma^{LT} = 0.5$, $\sigma^{KA} = \infty$ and $\sigma^{KT} = 0.25$). The same parameter values are applied to all states.

quantities I employed the Census Bureau's interim state population projections for 2015. In the baseline run of the model GDP is $15.9 trillion, slightly above DOE/EIA's (2006) projection, while the economy emits 8,174 million tons (MT) of CO_2, well above the corresponding estimate of 6,718 MT.[18]

3 Results

There are five components to the results. To orient the reader, I first present the characteristics of the baseline economy before examining the impacts of CO_2 emission taxes on the macroeconomy. I continue with an inquiry into the dynamics which underlie this aggregate picture, focusing first on the responses of industries to emission taxes, and then turning my attention to the influence of the tax on interstate terms of trade. Finally, I elucidate the impacts of the tax on regions and states, and provide insight into the precursors of the resulting geographic patterns of welfare change.

3.1 The no-policy baseline of the economy in 2015

Tables 2 and 3 illustrate key characteristics of the states in the BAU simulation. In Table 2, columns 1-3 indicate states' economic importance in terms of both production (GSP and gross output) and income (ASPI). The results highlight the difference between eqs. (3) and (4), with the gross output exceeding ASPI and ASPI exceeding GSP, both in the majority of states and at the level of the macroeconomy. Nevertheless, the three measures of size closely track one another, with the largest states being California, New York and Texas, and the smallest being N. Dakota, Vermont, Wyoming and Alaska. States' rankings differ markedly in terms of their per capita income, as shown in column 4. The wealthiest states are Washington DC, Connecticut and Massachusetts, while the poorest are Mississippi, Louisiana and New Mexico, with a coefficient of variation of 20 percent around the national average of $51,500.

Columns 5-7 tabulate the CO_2 emissions embodied in the total quantity of fossil fuels produced in each state, in those generated by the total consumption of fossil fuels, and households' consumption of fossil fuels, respectively.[19] Texas

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[18] This discrepancy can be easily remedied by appending trends in autonomous energy efficiency improvement (AEEI) to the coefficients on fossil fuels in the model's production and utility functions. However, Sue Wing and Eckaus (2006) argue that such trends exhibit marked divergence among industry sectors, which raises the question of whether they might be similarly differentiated across states as well. If so, it is hard to guess the correct interstate pattern of efficiency improvements without a detailed empirical investigation. My reluctance to employ such a quick fix is also philosophical—doing so implicitly reifies EIA's emission forecasts as "truth", even though they may substantially underestimate the projection of the U.S. historical trend (Sue Wing and Eckaus, 2006).

[19] Emissions according to first measure are $\sum_e \phi_e y_{e,s}$, by the second measure are $\sum_e \phi_e \left(\sum_j x_{e,j,s} + c_{e,s}\right)$, and by the third $\sum_e \phi_e c_{e,s}$.

and California are the dirtiest states in absolute terms using any of the three criteria, while the cleanest states in absolute terms are Washington DC, Rhode Island, Vermont and S. Dakota. Moreover, the results for the aggregate economy in columns 5 and 6 suggest that the U.S. in 2015 is a net importer of CO_2, primarily because of its consumption of foreign petroleum.

The first three columns of Table 3 give states' CO_2 emission intensity in terms of total (industry and household) fossil fuel consumption, total fossil fuel production, and final use of fossil fuels. The patterns of dirtiness in consumption and production exhibit marked differences from one another, with Wyoming and Alaska being among the most CO_2-intensive states, and Washington DC being among the least. All three criteria exhibit a high degree of dispersion, with the emission intensities of the cleanest and and dirtiest states differing by a factor of 16 in final uses, 57 in total consumption and over 270 in production.

The principal driver of this phenomenon is the highly skewed interstate distribution of production in energy sectors shown in columns 4-7. 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. In addition, the latter states, as well as Montana and S. Carolina, are relatively intensive in the production of electricity, whose emissions column 7 indicates are largely due to coal use. Combined with the fact these are all relatively poor states, these characteristics account for why their emission intensities are so high.

Finally, given that most of the 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 likely to be the bellwether for the economic impacts of emission limits. The high correlations between electricity intensity in column 5 and the emission intensities in column 1 and 3 (0.62 and 0.55, respectively), support this intuition. Moreover, column 7 shows that the bulk of emissions in the electric power sector come from coal use, especially in N. Dakota, Tennessee and W. Virginia.

3.2 Counterfactual simulations: aggregate results

to simulate the effect of climate policies, I construct a series of counterfactual shocks by levying carbon taxes that range between \$3/ton and \$100/ton CO_2. The Bingaman-Domenici (hereafter BD) proposal is simulated by specifying a tax at the level of the \$7/ton safety-valve limit. To approximate the more ambitious McCain-Lieberman (hereafter MCL) target, I assumed an aggregate emission cap set at the year-2004 level of 6150 $MTCO_2$. The dual emission tax consistent with the this target is \$56/ton CO_2, which lies within the range of estimates produced by Paltsev et al. (2003).[20]

[20] This result does not reflect the potential cost-savings from substituting opportunities to cheaply reduce emissions of non-CO_2 GHGs in place of relatively costly CO_2 emissions (see, e.g., Reilly et al., 1999), or the influence of the detailed provisions of the MCL proposal.

The summary of the macroeconomic consequences of these shocks in Figure 3 illustrates that that a broad range of taxes causes aggregate welfare to decline by only modest amounts, even though emissions are reduced from baseline levels by more than a third. The BD-equivalent tax would cut aggregate emissions by 6 percent at negligible cost to the economy, while the more substantial reductions generated by the MCL cap would incur much higher welfare costs, around half a percent of national income. It is also clear from the figure that the results at the aggregate level are unaffected by the pattern of recycling that is chosen.

3.3 Industry level impacts

To understand the drivers of the aggregate results it is useful to examine the response of industries to the tax. Sectors' CO_2 abatement responses are illustrated by Figure 4 in the form of marginal abatement cost (MAC) schedules. As in other studies of the U.S. economy (e.g., Sue Wing, 2004, 2005), the bulk of abatement comes from reductions in fossil fuel consumption by electricity generators and final use sectors, 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 figure summarizes industries' behavior in the case where the revenue from emission taxes is recycled to the state in which the residual emissions are generated, but the results for revenue recycling at the federal level are virtually identical.

These results suggest that states which are relatively specialized in coal or electricity production possess more low-cost abatement opportunities and therefore exhibit a more elastic abatement response. The same is true of populous states in which the structure of final demand is relatively intensive in fossil fuels. Figure 5 supports this intuition. Under the BD and MCL equivalent emission taxes, states' percentage cutbacks from BAU emission levels are positively associated with the coal, electricity, or transportation intensity of gross output in the baseline scenario, and negatively associated with their share of output in services, non-fuel mining and construction. It is also clear from Figure 5 that the choice of whether to recycle emission tax revenue at the state or federal levels exerts a only a very slight influence on the pattern of abatement.

3.4 Interstate terms of trade effects

We now examine the impact of emission taxes on states' terms of trade. The model's simplified structure makes such analysis difficult, as it is possible to distinguish only the production and consumption of commodities, *not* the import and export flows. Accordingly, for each state a pseudo-terms of trade measure ($PTOT$) was constructed using the weighted average of its producer prices as a proxy for its composite export price, and the weighted average of its consumer prices as a proxy for its composite import price:

$$PTOT_s = \sum_j \xi^X_{j,s} p_{j,s} \Big/ \left[\sum_e \xi^M_{e,s} \left(P_e + \phi_e \overline{\tau}^{CO_2}_s\right) + \sum_m \xi^M_{m,s} P_m\right]. \tag{7}$$

It was necessary to approximate imports and exports on a *net* basis. To do this, I classified each state as either as a net exporter of the i^{th} commodity—when the value of i's gross product ($v^{\text{Prod}}_{i,s}$) exceeded the value of its consumption ($v^{\text{Cons}}_{i,s}$) in the BAU solution—or as a net importer—when $v^{\text{Cons}}_{i,s} > v^{\text{Prod}}_{i,s}$.[21] States' import weights ($\xi^M_{i,s}$) are given by the shares of their net imports of each commodity in the value of total net imports:

$$\xi^M_{i,s} = \max\left[0, v^{\text{Cons}}_{i,s} - v^{\text{Prod}}_{i,s}\right] \Big/ \sum_i \max\left[0, v^{\text{Cons}}_{i,s} - v^{\text{Prod}}_{i,s}\right],$$

while their export weights ($\xi^X_{j,s}$) are given by the no-policy shares of each industry in the value of total net exports:

$$\xi^X_{i,s} = \max\left[0, v^{\text{Prod}}_{i,s} - v^{\text{Cons}}_{i,s}\right] \Big/ \sum_i \max\left[0, v^{\text{Prod}}_{i,s} - v^{\text{Cons}}_{i,s}\right].$$

The chief limitation of this weighting scheme is the bias introduced by the inability of the binary classification to account for intraindustry trade. Fortuitously, every state is a net importer of at least one kind of fossil fuel, which enables eq. (7) to capture the mechanism via which the rise in the consumer price of fossil fuels induced by the emission tax generates adverse terms of trade movements. The importance of this effect is apparent from Figure 6(a), in which the the mean of the interstate distribution of the change in $PTOT$ is consistently negative. The compressed interquartile range implies that outliers account for much of the dispersion around the mean. The composite price of imports rises in all states, with the smallest increases experienced by Delaware, Pennsylvania and Utah, and the largest by Nebraska, Alaska and N. Dakota. But at the same time the pass-through effect of abatement costs on producer prices also puts upward pressure on export prices (with the exception of Arizona, Washington DC, Nebraska and S. Dakota), so much so that one in five states experience improvements in their terms of trade. The dominance of the second effect is most pronounced in Wyoming, N. Dakota and W. Virginia.

Figure 6(b) shows that the baseline shares of coal and electricity in states' outputs are correlated with improvements in the terms of trade, while the shares of transportation and non-durable manufacturing are correlated with terms of trade declines. Interestingly, while coal- and electricity-intensive states such as W. Virginia and Montana experience terms-of-trade improvements, oil-intensive states such as Alaska and Louisiana see declines. The co-location of coal-mining and electric power production is the key to this outcome. For states which specialize in the production and export of fossil fuels, the attenuating effect of emission taxes on fuel demand precipitates a fall in the producer price of their main

[21] Here, $v^{\text{Prod}}_{i,s} = p^{\text{BAU}}_{j,s} y^{\text{BAU}}_{j,s}$ and $v^{\text{Cons}}_{i,s} = P^{\text{BAU}}_i \left(c^{\text{BAU}}_{i,s} + \sum_j x^{\text{BAU}}_{i,j,s}\right)$.

export industry, causing the numerator of (7) to contract. This impacts both coal- and oil-exporting states, but the essential difference is that the former also tend to export electric power. Electric generation's coal-intensive character means that emission taxes sharply increase the producer price of electricity, offsetting the fall in numerator of (7). Because electricity is a higher-value product than coal (cf. Table 3, columns 4 and 5), the result is an improvement in the terms of trade.

Not surprisingly, the recycling of emission tax revenues at the state or federal levels has only a small impact on $v_{i,s}^{\text{Cons}}$, $v_{i,s}^{\text{Prod}}$ and the changes in states' terms-of-trade. We now show that the choice of recycling scheme has significant implications for distribution of changes in income and welfare among states and regionals.

3.5 The incidence of CO_2 taxes at the state and regional levels

The breakdown of abatement and policy costs among the census divisions is summarized in Figure 7. The most vigorous abatement takes place in the E. South Central and W. North Central regions, while the E. North Central, W. South Central, Mountain and S. Atlantic regions make modest cutbacks, with the smallest abatement occurring in the Pacific, Mid-Atlantic and New England and states. Increasing levels of the tax see a concentration of abatement in the center of the country as the supply of emission reductions by the coastal states becomes inelastic. Consistent with the results thus far, the choice of recycling scheme has little effect on the interregional distribution of abatement, with states' trajectories exhibiting similar horizontal components in panels (a) and (b).

As suggested by the dispersion of terms-of-trade effects, there is considerable variation in the costs of these policies among states and regions, with the pattern of welfare changes being strongly influenced by revenue recycling. Panel (a) shows that when emission tax revenues are recycled in situ, the central regions of the U.S. gain for modest levels of the tax, while the South Central and W. North Central regions see their income continue to rise, even as taxes grow large. The N. Central and particularly the Mountain and S. Atlantic regions experience modest reductions in income, while the New England, Mid Atlantic and Pacific regions sustain large losses. Panel (b) indicates that federal revenue recycling generates a very different picture. In this case, small increases in income are enjoyed by the eastern seaboard regions for modest levels of the tax, and by New England and the S. Atlantic states for all tax rates considered. The N. Central, E. South Central, Pacific and Mountain regions all experience modest declines in income, whereas the W. South Central region sees large losses. Interestingly, the interregional dispersion of income effects is larger with federal recycling. I argue below that this result is primarily due to differences in the quantity of carbon-tax revenue recycled to states with the highest costs of abatement.

The implications of these patterns for the current national emission reduction proposals are captured by the summary of the regional impacts of BD- and

MCL-equivalent taxes in Figure 8. The distribution of emission reductions in panel (a) is similar for the two policies, save for some redistribution of abatement from the Atlantic states to the South Central region. Panel (b) indicates that with state-level revenue recycling the costs of both policies are concentrated in the eastern and western coastal states (the latter in particular), while the South Central regions see small gains. In panel (c) recycling emission tax revenues at the federal level causes eastern states to gain (or, in the case of the Mid-Atlantic region, suffer negligible losses), while the west and center of the country generally experience modest reductions in income. The exception is the W. South Central states, where losses are concentrated, but not to the same degree as the Pacific states under in situ revenue recycling.

The underlying state-level impacts are shown in Table 4. The percentage reductions in emissions summarized in the first column indicate that abatement is concentrated in states which are intensive in fossil fuels (N. Dakota, Alaska, Mississippi, Kentucky and W. Virginia), while the least occurs in the states with little coal-fired electric power production (e.g., Maine, Vermont, New Hampshire and New York). While these results correspond to the recycling of emission tax revenue at the state level, those generated under the federal revenue recycling rule are very similar.

The second and third set of columns tabulate the effects on per-capita personal income and economic welfare. When tax revenue is recycled at the state level, Rhode Island, Arizona and California see the largest declines, while Wyoming, Alaska and W. Virginia see the largest gains. The $7/ton tax increases households' annual income by as much as 0.9 percent, which translates into additional income of $189 in W. Virginia, $216 in Alaska, and $384 per person in Wyoming. By contrast, the states hit hardest by the tax suffer only small welfare losses: no more than one-tenth of one percent, for a reduction in annual income of less than $60 per person. Under the $56/ton tax, W. Virginia, N. Dakota and Wyoming are the biggest beneficiaries, while Vermont, New Hampshire and Connecticut experience the biggest losses. On a per capita basis, the gains and losses under the MCL policy can be as much as two orders of magnitude larger than those which obtain under the BD emission limit, with W. Virginia enjoying the largest gains ($2512 per capita) and Arkansas suffering the largest losses ($876 per capita).

Federal revenue recycling results in strikingly different changes in state incomes. Now, under both the BD and MCL policies the principal beneficiaries are the jurisdictions which receive the bulk of federal spending (Washington DC, Maryland and Virginia), while the principal donors are fossil-fuel producing states (Wyoming, N. Dakota and Alaska). With the $7/ton emission tax the first group of states see their annual incomes increase by 0.2-0.5 percent ($214-$285 per capita), while the second group experiences a decline of 0.5-0.8 percent ($126-$481 per capita). Under the $56/ton tax these impacts are more pronounced, with the former states' annual incomes increasing by 1.2-3.9 percent ($657-$2940 per capita), and those of the latter states falling by 2.8-5.3 percent ($1190-$2040 per capita).

Table 5 elucidates the origins of these impacts by decomposing the change in per-capita ASPI into changes in factor remuneration and recycled revenue from state and federal taxes according to eq. (4). Column 1 shows that without exception industry as a whole is made worse off, and that the quantity of abatement closely tracks the declines in factor income. This quantity, $\Delta(RK_s + W_s L_s)$, is the primary economic burden of abatement, whose absolute magnitude is smallest in Washington DC, Hawaii and Rhode Island, and largest in Wyoming, N. Dakota and Alaska. As before, these figures are for state revenue recycling, but the impacts for federal recycling are very similar.

Changes in tax revenue recycled to the states under the different combinations of emission limits and recycling schemes are shown in the second and third set of columns. Recall that when revenue is recycled at the state (federal) level, CTR_s—totaling \$54 billion under Bingaman-Domenici and \$345 billion in the case of McCain-Lieberman—becomes a component of state (federal) tax revenue.[22] One would therefore expect to see a sharp increase in the magnitude of the revenue stream which corresponds to the locus of recycling, and this is exactly what the results show. These increases are concentrated in fossil-fuel exporting states which have high residual emissions with in situ recycling, and in the states which command the largest fraction of federal spending when there is federal recycling. If revenues are recycled at federal level, the changes in revenue from pre-existing state taxes are generally small and their contributions to income equivocal: positive in Washington DC, Connecticut and New Hampshire, negative in Alaska, N. Dakota and W. Virginia. Conversely, if emission taxes are recycled within the states, the revenue from pre-existing federal taxes exhibits modest declines across the board, with the biggest reductions occurring in N. Dakota, Washington DC and Alaska, and the smallest in New Hampshire, Vermont and California. In all cases, an increase in the emission tax serves to amplify the magnitude of the various components of change—be they positive or negative—in a monotonic fashion.

The central implication of these results is that apart from the stringency of the tax on emissions, the scheme by which the resulting revenue stream is recycled to households is the single most important influence on the geographic distribution of the income effects of climate change policy. The clear message of Table 5 is that states' fortunes under either recycling scheme depend on whether their receipts of recycled emission tax revenue exceed or fall short of their primary abatement burdens. In terms of eq. (4), and ignoring for simplicity the changes in revenue from pre-existing taxes, the relevant conditions are whether $\Delta(RK_s + W_s L_s) \gtrless \overline{\tau}^{CO_2}\mathscr{E}_s$ or $\Delta(RK_s + W_s L_s) \gtrless \omega_s \sum_s \overline{\tau}^{CO_2}\mathscr{E}_s$. Since $\Delta(RK_s + W_s L_s)$ is determined by the emission tax, for a given value of $\overline{\tau}^{CO_2}$, the larger (smaller) the value of the ratio $\mathscr{E}_s / \left(\omega_s \sum_s \mathscr{E}_s\right)$ the greater the likelihood that state s will enjoy a net welfare gain when revenue is recycled at the state (federal) level. Indeed, the states with the largest values of this ratio (Louisiana, N. Dakota, Alaska

[22] To put these numbers in context, the total value of pre-existing state and federal taxes are \$972 and \$2135 billion (respectively) in the BAU scenario, \$971 and \$2128 billion with the BD tax, and \$963 and \$2084 billion under the MCL-equivalent tax.

and Wyoming) are precisely the ones which gain the most under state recycling, while those with the smallest values (Rhode Island, Maryland and Washington DC) are precisely the states which gain the most under federal recycling.

4 Concluding Remarks

This paper has investigated the regional incidence of policies to limit U.S. CO_2 emissions by constructing a geographically detailed CGE model of the U.S. economy which is then used to simulate the effects of emission taxes on states and regions. The main findings may be summarized as follows:

1. The emission reductions under the Bingaman-Domenici and McCain-Lieberman proposals incur macroeconomic costs which are at worst modest. It is estimated that the former policy reduces aggregate emissions by six percent at negligible cost to the economy, while latter reduces aggregate emissions by one third at a cost of around half a percent of national income. These aggregate impacts are unaffected by the scheme used to recycle emission tax revenues.
2. Consistent with previous studies, the final demand and electric power sectors are responsible for the bulk of emission reductions, and states' relative specialization in these industries determines the geographic distribution of both cheap abatement opportunities and primary abatement costs.
3. Fossil-fuel producing states' terms of trade tend to deteriorate due to the contraction in primary energy demand induced by an emission tax, while states with concentrations of energy-intensive sectors see terms-of-trade improvements as the burden of the tax increases the unit costs of energy-intensive production. The latter effect, combined with the co-location of coal mining and electric power production, is responsible for counterintuitive improvements in coal-intensive states' terms of trade.
4. The method for recycling emission tax revenue is a key driver of the geographic distribution of the income effects of climate policy. When emission tax revenues are recycled in situ, both the BD and MCL policies net gains which are concentrated in fossil-fuel intensive states, and incur net costs which are generally small in magnitude but widely diffused among large, highly energy-consuming states. By contrast, recycling emission taxes at the federal level raises the incomes of states whose shares of federal spending are disproportionally large, while imposing the highest costs on fossil-fuel producers. The implications for the interregional distribution of policy costs are as follows: in the first case the states in the central regions of the country enjoy modest gains while those in New England and especially the Pacific seaboard see significant losses, while in the second the pattern is reversed: New England and the Atlantic states gain while losses are concentrated in the central regions, especially the W. South Central states. The key to this outcome is the magnitude of a state's own residual emissions compared to its "share" of aggregate residual emissions, as determined by its share of federal spending.

These results advance our understanding of a heretofore neglected but crucially important aspect of U.S. climate policy, namely the consequences of allowing states to recycle locally-raised tax revenue within their own borders, versus requiring them to treat these funds as federal revenues to disbursed among all jurisdictions as federal spending. The resulting patterns of geographic incidence have important political economy implications. Elected state representatives are the ones who will ultimately craft legislation to limit aggregate GHG emissions, but they face strong incentives to avoid the incidence of abatement costs falling on their own constituents. The uphill battle in Congress faced by previous versions of the Bingaman-Domenici and McCain-Lieberman proposals is symptomatic of this tension. But although one might imagine that these propsals will continue to be blocked by a coalition of high-abatement-cost, fossil-fuel intensive states, the fact that differences in recycling schemes strongly influence the interstate distribution of income effects suggests that it may be possible to facilitate consensus by designing a system of income transfers to compensate the states hardest hit by the cap. In particular, this paper has rigorously demonstrated that recycling emission tax revenues at the state level can generate significant welfare improvements in the very states whose primary abatement burdens are highest, while incurring modest losses elsewhere. More work is needed to investigate the implications of this result for the design of a national climate change policy.

Appendix: 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)
$y_{j,s}$	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
$\theta_{l,j,s}$	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
$\overline{\tau}_{j,s}^{L,t}$	Industry j/state s pre-existing labor taxes, $t \in \{$S (state), F (federal)$\}$
$\overline{\tau}_{j,s}^{K,t}$	Industry j/state s pre-existing capital taxes, $t \in \{$S (state), F (federal)$\}$
$\overline{\tau}_{j,s}^{Y,t}$	Industry j/state s pre-existing production taxes, $t \in \{$S (state), F (federal)$\}$
$\overline{\tau}^{CO_2}$	Aggregate CO_2 tax
ϕ_e	Energy commodity e stoichiometric CO_2 coefficient
ω_s	State s share of aggregate federal government spending in the base year

Elasticities of substitution and transformation

σ^E	Substitution among fuels	1.0
σ^{VA}	Capital-labor substitution	1.0
σ_j^A	Industry j interstate Armington substitution	1-5
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, dual to the $N \times S$ activity levels of industries within states:

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

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

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

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

$$P^U_s = \left[\sum_e \alpha^{\sigma^C}_{e,s} (P_e + \phi_e \overline{\tau}^{\mathrm{CO_2}})^{1-\sigma^C} + \sum_m \alpha^{\sigma^C}_{m,s} P^{1-\sigma^C}_m \right]^{1/(1-\sigma^C)} \quad \perp \quad U_s \qquad \text{(ZP3)}$$

4. 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:

$$\left(\sum_o \lambda^{\sigma^{LA}}_{o,s} W^{1-\sigma^{LA}}_o \right)^{1/(1-\sigma^{LA})} = \left(\sum_j \gamma^{\sigma^{LT}}_{j,s} w^{1-\sigma^{LT}}_{j,s} \right)^{1/(1-\sigma^{LT})} \quad \perp \quad A^L_s \qquad \text{(ZP4)}$$

5. 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:

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

Market clearance conditions

1. N conditions defining aggregate supply-demand balance for commodities, dual to the N aggregate commodity prices:

$$Y_e = \sum_s \left[\sum_j \left\{ (1 + \overline{\tau}^{Y,\mathrm{S}}_{j,s} + \overline{\tau}^{Y,\mathrm{F}}_{j,s}) \frac{\theta^{\sigma^E}_{e,j,s}}{\theta_{E,j,s}} \left(\frac{p_{j,s}}{P_e + \phi_e \overline{\tau}^{\mathrm{CO}_2}} \right)^{\sigma^E} y_{j,s} \right\} + \alpha^{\sigma^C}_{e,s} \left(\frac{P^U_s}{P_e + \phi_e \overline{\tau}^{\mathrm{CO}_2}} \right)^{\sigma^C} U_s + \overline{n}_{e,s} \right] \quad \perp \quad P_e \tag{MC1a}$$

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

2. $N \times S$ conditions defining supply-demand balance for industries' outputs, dual 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, dual to the S average state wage levels:

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

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

$$\gamma^{\sigma^{LT}}_{j,s} \left(\frac{W_s}{w_{j,s}} \right)^{\sigma^{LT}} A^L_s = (1 + \overline{\tau}^{Y,\mathrm{S}}_{j,s} + \overline{\tau}^{Y,\mathrm{F}}_{j,s}) \frac{\theta_{l,j,s}}{\theta_{VA,j,s}} \left\{ (1 + \overline{\tau}^{L,\mathrm{S}}_{j,s} + \overline{\tau}^{L,\mathrm{F}}_{j,s}) w_{j,s} \right\}^{\theta_{l,j,s}-1} \times \left\{ (1 + \overline{\tau}^{K,\mathrm{S}}_{j,s} + \overline{\tau}^{K,\mathrm{F}}_{j,s}) r_{j,s} \right\}^{\theta_{K,j,s}} \quad \perp \quad w_{j,s} \tag{MC4}$$

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

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

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

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

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

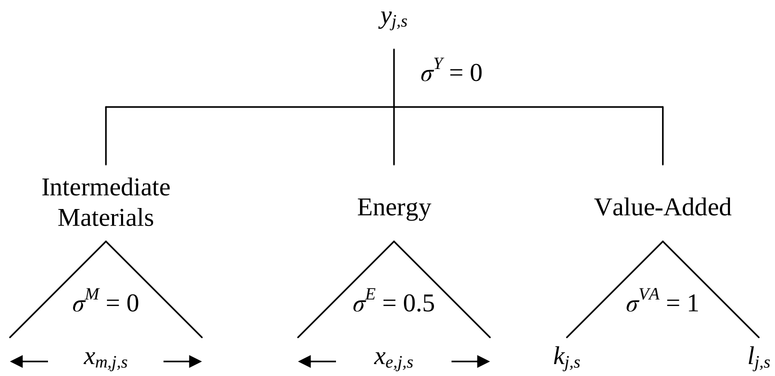
$$
\begin{aligned}
U_s = W_s L_s + RK_s + \sum_i P_i \overline{n}_{i,s} &+ \left(\sum_j \overline{\tau}^{L,\mathrm{S}}_{j,s} w_{j,s} l_{j,s} + \sum_j \overline{\tau}^{K,\mathrm{S}}_{j,s} r_{j,s} k_{j,s} + \sum_j \overline{\tau}^{Y,\mathrm{S}}_{j,s} p_{j,s} y_{j,s} \right) \\
&+ \omega_s \sum_s \left(\sum_j \overline{\tau}^{L,\mathrm{F}}_{j,s} w_{j,s} l_{j,s} + \sum_j \overline{\tau}^{K,\mathrm{F}}_{j,s} r_{j,s} k_{j,s} + \sum_j \overline{\tau}^{Y,\mathrm{F}}_{j,s} p_{j,s} y_{j,s} \right) \\
&+ \begin{cases} \overline{\tau}^{\mathrm{CO_2}} \mathscr{E}_s & \text{State revenue recycling} \\ \overline{\tau}^{\mathrm{CO_2}} \omega_s \sum_s \mathscr{E}_s & \text{Federal revenue recycling} \end{cases} \quad \perp \quad P^U_s \qquad \text{(IB)}
\end{aligned}
$$

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. State-level emissions are given by the total use of fossil fuels, weighted by the corresponding emission factors:

$$
\begin{aligned}
\mathscr{E}_s = \sum_e \phi_e \Bigg[\sum_j \Bigg\{ (1 + \overline{\tau}^{Y,\mathrm{S}}_{j,s} + \overline{\tau}^{Y,\mathrm{F}}_{j,s}) \frac{\theta^{\sigma^E}_{e,j,s}}{\theta_{E,j,s}} \left(\frac{p_{j,s}}{P_e + \phi_e \overline{\tau}^{\mathrm{CO_2}}} \right)^{\sigma^E} y_{j,s} \Bigg\} \\
+ \alpha^{\sigma^C}_{e,s} \left(\frac{P^U_s}{P_e + \phi_e \overline{\tau}^{\mathrm{CO_2}}} \right)^{\sigma^C} U_s \Bigg]
\end{aligned}
$$

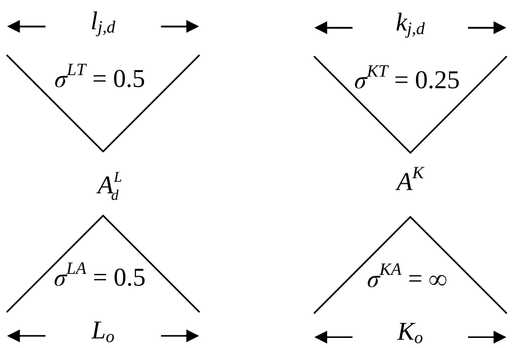
General equilibrium
The excess demand correspondence of the economy is made up of the $(N \times S + N + 2S + 1)$-vector of zero profit conditions (ZP1)-(ZP5), the $(3(N \times S) + N + S + 1)$-vector of market clearance conditions (MC1)-(MC6), and the S income balance conditions (IB). The resulting 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, $\mathbf{b} = \{p_{j,s}, P_i, W_s, w_{j,s}, R, r_{j,s}, P^U_s, y_{j,s}, Y_i, A^L_s, A^K, U_s\}$.

Fig. 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

Fig. 2 Benchmark Year-2000 Interregional Social Accounts (Billion $)

Northeast	A	B	C	Fin. Use	Total
A	7.03	4.09	30.11	24.53	65.76
B	32.42	6.97	28.09	14.94	82.42
C	17.27	27.19	1531.67	2142.29	3718.42
L	2.79	7.59	1093.53		1103.92
K	3.71	14.90	551.23		569.84
LTR^{S}	0.08	0.24	35.94		36.26
LTR^{F}	0.43	1.16	167.33		168.91
KTR^{S}	0.16	0.63	25.15		25.94
KTR^{F}	0.95	3.70	141.41		146.06
YTR^{S}	0.85	5.03	74.71		80.59
YTR^{F}	0.08	0.40	5.54		6.02
Total	65.76	71.89	3684.72	2181.76	6004.13

South	A	B	C	Fin. Use	Total
A	2.02	1.20	4.37	3.40	10.99
B	4.14	0.90	3.91	2.18	11.13
C	2.21	3.52	213.96	312.61	532.31
L	0.78	1.91	164.50		167.19
K	1.22	3.74	88.70		93.66
LTR^{S}	0.02	0.03	3.14		3.19
LTR^{F}	0.10	0.25	20.92		21.26
KTR^{S}	0.02	0.07	2.11		2.20
KTR^{F}	0.19	0.63	16.17		16.99
YTR^{S}	0.24	0.88	11.29		12.41
YTR^{F}	0.05	0.31	2.31		2.68
Total	10.99	13.46	531.38	318.19	874.01

Midwest	A	B	C	Fin. Use	Total
A	9.53	6.46	23.60	23.36	62.95
B	28.59	6.14	26.57	14.98	76.28
C	15.22	24.08	1464.28	2148.03	3651.62
L	3.18	8.87	1159.23		1171.28
K	3.90	16.03	563.93		583.86
LTR^{S}	0.09	0.26	33.89		34.24
LTR^{F}	0.41	1.12	146.31		147.83
KTR^{S}	0.15	0.64	22.75		23.54
KTR^{F}	0.77	3.11	110.75		114.62
YTR^{S}	0.96	5.33	69.12		75.41
YTR^{F}	0.17	0.89	11.47		12.53
Total	62.95	72.94	3631.90	2186.37	5954.16

West	A	B	C	Fin. Use	Total
A	0.96	0.47	1.81	4.05	7.29
B	3.18	0.69	2.91	1.55	8.33
C	1.69	2.66	161.77	221.82	387.95
L	0.36	0.83	116.30		117.49
K	0.71	1.66	67.64		70.01
LTR^{S}	0.01	0.03	3.86		3.90
LTR^{F}	0.05	0.12	16.77		16.94
KTR^{S}	0.03	0.06	2.74		2.83
KTR^{F}	0.13	0.29	12.35		12.77
YTR^{S}	0.16	0.53	7.23		7.92
YTR^{F}	0.02	0.06	0.82		0.90
Total	7.29	7.39	394.21	227.42	636.31

A: Fossil Fuels; B: Non-Fossil Energy Sectors; C: Non-Energy Sectors; L: Labor; K: Capital; LTR^{S} and LTR^{F}: revenues from State and Federal taxes on labor; KTR^{S} and KTR^{F}: revenues from State and Federal taxes on capital; YTR^{S} and YTR^{F}: revenues from State and Federal taxes on production.

Fig. 3 Macroeconomic Impacts of CO_2 Taxes in 2015

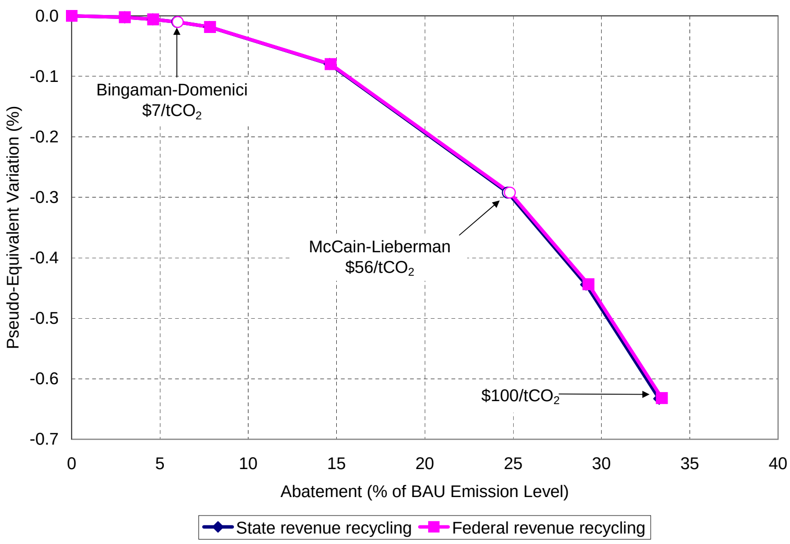
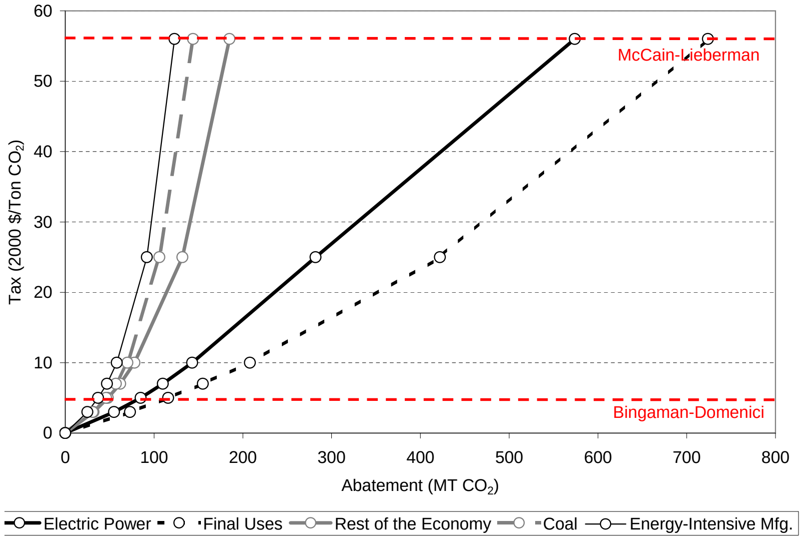
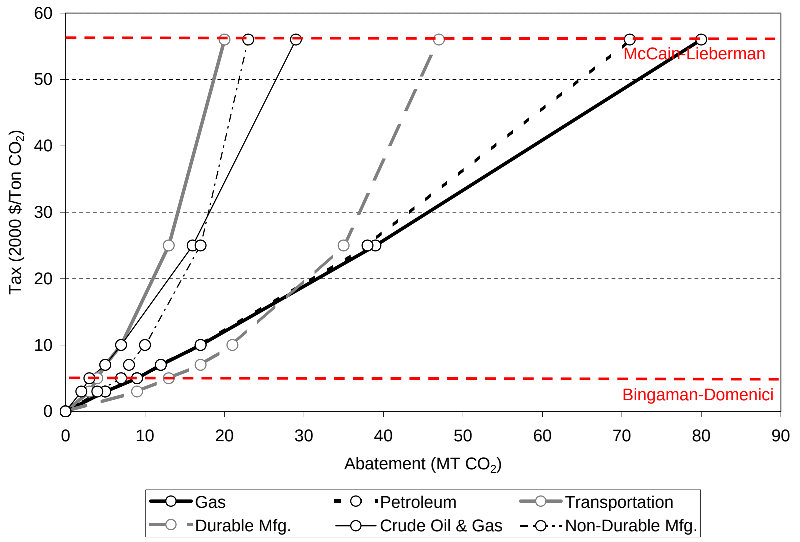


Fig. 4 Industry Marginal Abatement Cost Curves for the U.S. Economy in 2015



(a) Large abaters



(b) Small abaters

Fig. 5 Implications of Industrial Composition for States' Abatement

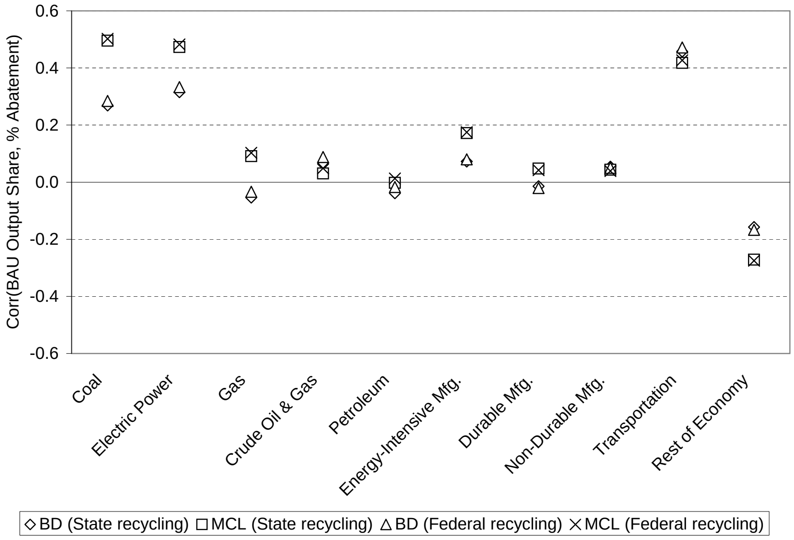
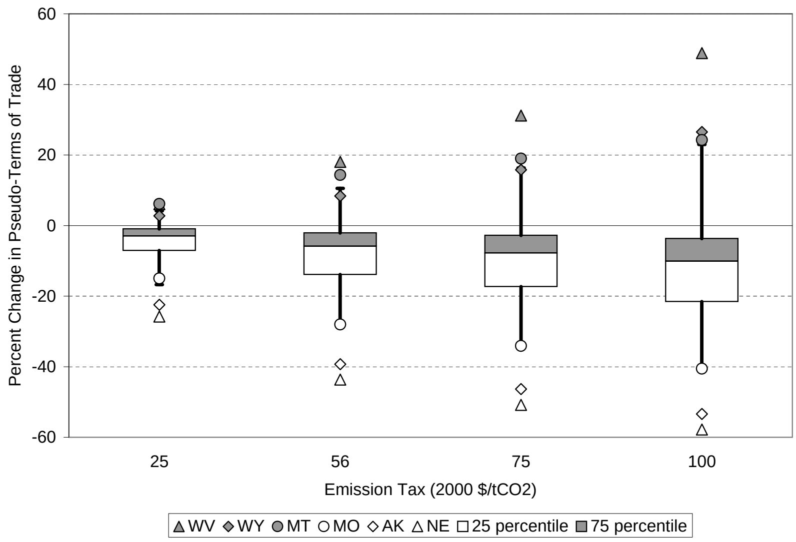
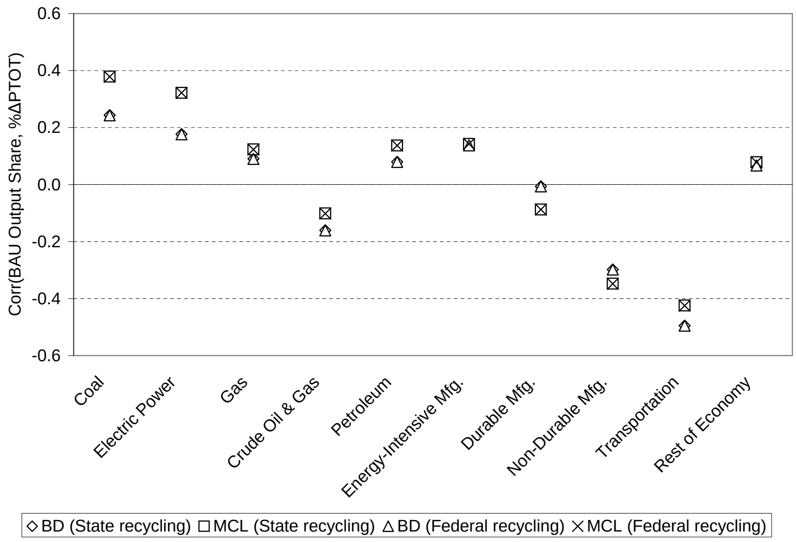


Fig. 6 Changes in the Terms of Trade

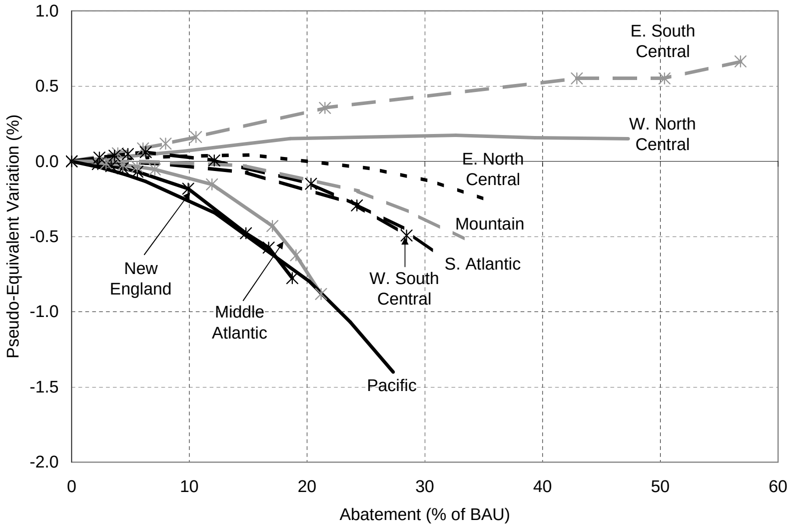


(a) Interstate distribution of changes in the terms of trade
(error bars indicate 5- and 95-percentiles)

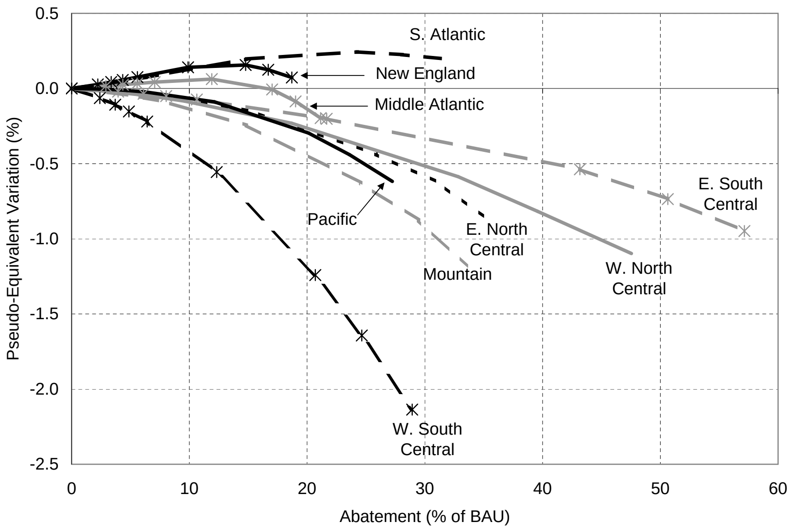


(b) Correlation b/w BAU share of output and states' abatement

Fig. 7 Regional Abatement and Welfare Costs in 2015

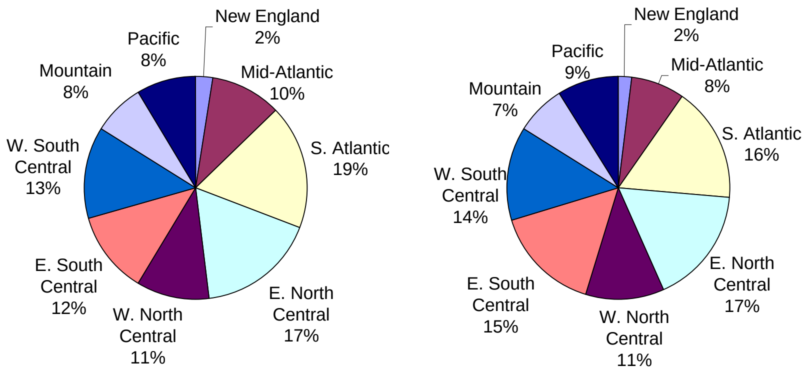


(a) State revenue recycling



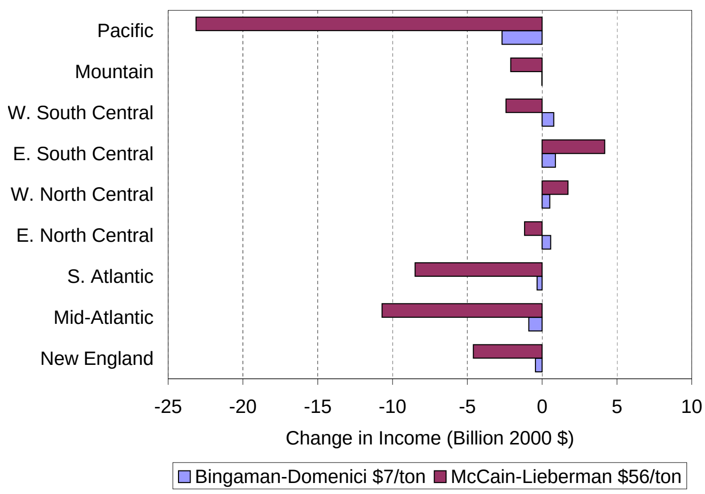
(b) Federal revenue recycling

Fig. 8 Regional Impacts of Recent Climate Policy Proposals

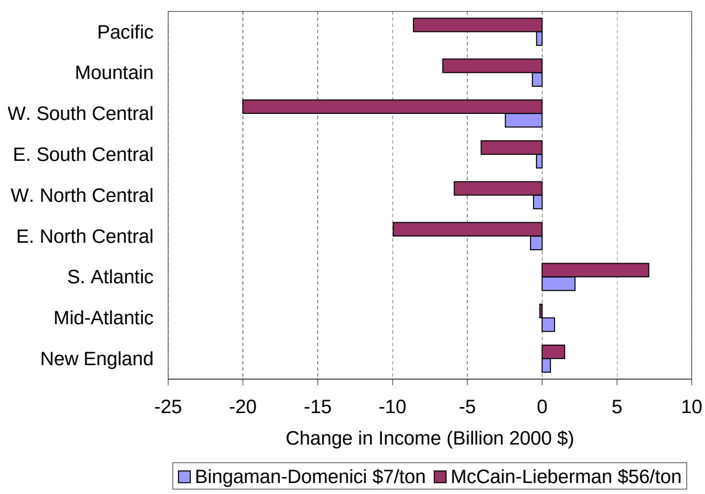


Bingaman-Domenici McCain-Lieberman

(a) The distribution of abatement



(b) The distribution of income effects (State revenue recycling)



(c) The distribution of income effects (Federal revenue recycling)

Table 1 Sectors and Commodities in the CGE Model

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

Table 2 Selected State Characteristics in the 2015 Pre-Tax Equilibrium

	1. GSP (Bn \$)	2. Gross Output (Bn \$)	3. ASPI (Bn\$)	4. ASPI per capita ('000\$)	5. CO_2: F.F. Consumption (MT)	6. CO_2: F.F. Production (MT)	7. CO_2: Hhold. F.F. Cons. (MT)
AL	158	321	193	39.0	196	127	57
AK	24	54	31	38.8	91	16	18
AZ	244	531	303	52.2	129	76	61
AR	85	186	108	36.8	90	55	33
CA	1,819	4,081	2,256	54.5	560	1,045	294
CO	234	522	294	60.9	108	166	40
CT	190	476	259	73.9	69	107	8
DE	42	102	47	56.9	21	32	5
DC	88	105	45	76.0	11	14	1
FL	629	1,550	921	49.8	372	269	175
GA	400	820	448	48.7	213	174	82
HI	51	101	58	37.5	29	17	14
ID	54	117	67	41.2	30	19	10
IL	556	1,189	682	53.2	305	354	89
IN	250	503	295	46.0	342	155	66
IA	119	243	143	47.8	131	45	23
KS	109	226	133	45.4	90	59	31
KY	154	310	179	42.2	210	287	50
LA	146	281	166	34.3	235	228	92
ME	45	103	60	44.1	35	23	2
MD	242	583	346	59.1	117	127	25
MA	368	858	467	71.0	117	193	16
MI	370	810	480	48.4	229	191	84
MN	247	550	307	58.2	126	125	47
MS	82	168	104	34.3	144	41	55
MO	220	460	266	44.3	196	118	51
MT	27	63	38	35.5	42	50	17
NE	68	148	85	45.9	72	28	23
NV	115	250	140	64.3	79	39	40
NH	68	150	85	62.1	30	26	0
NJ	428	1,055	599	67.1	189	246	51
NM	68	136	77	33.7	79	94	31
NY	999	2,257	1,238	65.4	377	507	39
NC	378	787	432	48.9	210	156	54
ND	24	50	29	41.5	72	33	14
OH	454	923	542	46.8	297	229	95
OK	114	247	150	39.7	122	81	52
OR	181	353	197	49.3	74	54	32
PA	506	1,093	652	52.4	333	395	68
RI	45	106	58	54.5	16	24	3
SC	149	305	182	41.6	121	59	39
SD	33	66	38	45.4	21	10	7
TN	245	485	282	44.3	181	97	51
TX	988	2,085	1,188	48.9	899	813	368
UT	99	189	107	40.0	73	108	24
VT	22	57	33	50.3	13	10	0
VA	359	792	435	54.9	198	239	43
WA	280	621	355	50.4	125	162	58
WV	47	107	68	36.9	134	259	27
WI	220	490	282	49.5	149	101	37
WY	20	49	28	44.0	74	181	15
U.S.	12,862	28,113	15,979	51.5	8,174	8,064	2,617

Table 3 Selected State Characteristics in the 2015 Pre-Tax Equilibrium (Continued)

	1. F.F. Cons. ÷ Gross Output (kg/$)	2. F.F. Prod. ÷ GSP (kg/$)	3. Hhold. F.F. Cons. ÷ ASPI (kg/$)	4. Coal Shr. of GSP (%)	5. Elec. Shr. of GSP (%)	6. Oil Shr. of GSP (%)	7. Coal Shr. of Elec. F.F. Input (%)
AL	0.61	0.80	0.29	0.20	1.94	0.34	98.8
AK	1.67	0.66	0.59		0.80	1.61	58.1
AZ	0.24	0.31	0.20		1.27	0.01	88.3
AR	0.48	0.65	0.31		1.79	0.61	98.3
CA	0.14	0.57	0.13		0.93	0.40	6.5
CO	0.21	0.71	0.13	0.13	1.16	0.07	95.0
CT	0.14	0.56	0.03		1.09	0.09	53.8
DE	0.21	0.76	0.11		1.23		79.8
DC	0.10	0.16	0.02		0.62	0.02	0.0
FL	0.24	0.43	0.19		1.18	0.05	69.4
GA	0.26	0.43	0.18		1.19	0.06	98.4
HI	0.28	0.32	0.25		1.48		41.2
ID	0.26	0.35	0.16		1.77		0.0
IL	0.26	0.64	0.13	0.04	1.51	0.39	99.1
IN	0.68	0.62	0.23	0.07	1.63	0.28	99.6
IA	0.54	0.38	0.16		1.49		99.8
KS	0.40	0.55	0.23		1.68	0.40	98.9
KY	0.68	1.87	0.28	0.81	1.46	0.24	99.9
LA	0.84	1.57	0.55	0.01	2.57	3.60	85.0
ME	0.34	0.51	0.03		1.58	0.08	6.1
MD	0.20	0.52	0.07	0.01	1.55	0.08	95.0
MA	0.14	0.52	0.03		1.13	0.07	61.4
MI	0.28	0.52	0.18		1.47	0.14	95.9
MN	0.23	0.51	0.15		0.97	0.25	98.0
MS	0.86	0.50	0.53		2.12	1.32	93.8
MO	0.43	0.54	0.19	0.03	1.28	0.18	99.3
MT	0.67	1.89	0.44	0.49	2.93	1.25	97.5
NE	0.49	0.41	0.27		1.13		99.7
NV	0.32	0.34	0.29		1.51	0.02	74.9
NH	0.20	0.38	0.00		1.62	0.02	94.3
NJ	0.18	0.57	0.08		1.39	0.61	94.6
NM	0.58	1.38	0.40	0.57	2.30	0.46	96.7
NY	0.17	0.51	0.03		1.06	0.13	57.3
NC	0.27	0.41	0.12		1.28	0.06	99.3
ND	1.44	1.40	0.47	0.65	2.42		99.9
OH	0.32	0.51	0.18		1.63	0.38	99.7
OK	0.50	0.71	0.35		1.99	1.23	94.5
OR	0.21	0.30	0.17		1.14	0.03	73.4
PA	0.30	0.78	0.10	0.17	2.03	0.26	97.6
RI	0.15	0.54	0.06		1.60		0.0
SC	0.39	0.40	0.22		2.82	0.04	99.3
SD	0.32	0.29	0.19		1.40		96.9
TN	0.37	0.40	0.18	0.01	0.52	0.11	99.4
TX	0.43	0.82	0.31	0.03	2.39	0.96	80.6
UT	0.39	1.09	0.23	0.39	1.62	0.90	99.2
VT	0.23	0.46	0.00		1.84		0.0
VA	0.25	0.67	0.10	0.09	1.16	0.05	96.8
WA	0.20	0.58	0.16	0.02	1.12	0.54	82.9
WV	1.25	5.56	0.39	2.98	4.67	0.58	99.8
WI	0.30	0.46	0.13		1.26		99.1
WY	1.52	8.93	0.52	4.65	5.62	0.96	99.9
U.S.	0.51	0.63	0.16	0.06	1.42	0.34	93.4

Table 4 Impacts of Bingaman-Domenici and McCain-Lieberman Equivalent CO_2 Taxes

	1. Abatement		2. Change in ASPI Per Capita				3. Pseudo-Equivalent Variation			
	State Recycling (%)		State Recycling ($)		Federal Recycling ($)		State Recycling (%)		Federal Recycling (%)	
	BD	MCL	BD	MCL	BD	MCL	BD	MCL	BD	MCL
AL	-7	-30	51	249	-10	-166	0.13	0.64	-0.03	-0.42
AK	-9	-25	216	1136	-285	-2037	0.56	2.92	-0.73	-5.24
AZ	-6	-23	-33	-309	-10	-188	-0.06	-0.59	-0.02	-0.36
AR	-6	-23	29	-876	-4	-129	0.08	-2.38	-0.01	-0.35
CA	-4	-19	-60	-494	-6	-152	-0.11	-0.90	-0.01	-0.28
CO	-5	-19	-38	-347	-25	-289	-0.06	-0.57	-0.04	-0.47
CT	-6	-19	-36	-327	23	29	-0.05	-0.44	0.03	0.04
DE	-5	-19	15	-18	9	-81	0.03	-0.03	0.02	-0.14
DC	-6	-19	28	58	481	2939	0.04	0.08	0.64	3.88
FL	-6	-23	-39	-363	-3	-135	-0.08	-0.73	-0.01	-0.27
GA	-6	-21	-4	-144	-2	-128	-0.01	-0.30	0.00	-0.26
HI	-6	-22	-5	-115	68	328	-0.01	-0.31	0.18	0.87
ID	-7	-23	-12	-154	14	-9	-0.03	-0.37	0.03	-0.02
IL	-6	-20	-11	-164	-10	-159	-0.02	-0.31	-0.02	-0.30
IN	-8	-41	95	482	-103	-779	0.21	1.05	-0.22	-1.69
IA	-8	-30	68	334	-54	-486	0.14	0.70	-0.11	-1.02
KS	-6	-24	14	12	-22	-249	0.03	0.03	-0.05	-0.55
KY	-8	-56	79	426	-56	-405	0.19	1.01	-0.13	-0.96
LA	-4	-20	70	277	-70	-595	0.21	0.81	-0.20	-1.73
ME	-1	-6	8	-100	35	43	0.02	-0.23	0.08	0.10
MD	-6	-21	-26	-293	161	885	-0.04	-0.50	0.27	1.50
MA	-5	-17	-41	-384	46	154	-0.06	-0.54	0.06	0.22
MI	-6	-21	-4	-117	4	-74	-0.01	-0.24	0.01	-0.15
MN	-5	-19	-26	-283	-37	-378	-0.04	-0.49	-0.06	-0.65
MS	-9	-39	75	354	-30	-316	0.22	1.03	-0.09	-0.92
MO	-7	-33	28	98	7	-70	0.06	0.22	0.02	-0.16
MT	-6	-23	41	197	-30	-293	0.12	0.56	-0.09	-0.82
NE	-8	-46	59	299	-27	-281	0.13	0.65	-0.06	-0.61
NV	-6	-23	-26	-329	-133	-1007	-0.04	-0.51	-0.21	-1.56
NH	-3	-11	-15	-226	1	-135	-0.02	-0.36	0.00	-0.22
NJ	-6	-17	-42	-392	-6	-187	-0.06	-0.58	-0.01	-0.28
NM	-6	-24	42	208	28	86	0.12	0.62	0.08	0.26
NY	-4	-15	-30	-335	29	28	-0.05	-0.51	0.04	0.04
NC	-6	-20	9	-62	10	-57	0.02	-0.13	0.02	-0.12
ND	-12	-64	189	1629	-242	-1189	0.45	3.93	-0.58	-2.87
OH	-6	-19	7	-69	5	-79	0.02	-0.15	0.01	-0.17
OK	-6	-23	7	-39	-21	-247	0.02	-0.10	-0.05	-0.62
OR	-5	-21	-26	-240	-12	-174	-0.05	-0.49	-0.02	-0.35
PA	-7	-19	3	-69	27	78	0.01	-0.13	0.05	0.15
RI	-4	-16	-32	-320	94	465	-0.06	-0.59	0.17	0.86
SC	-6	-21	30	140	22	59	0.07	0.34	0.05	0.14
SD	-6	-20	-4	-115	34	98	-0.01	-0.25	0.07	0.22
TN	-8	-45	11	11	0	-92	0.03	0.03	0.00	-0.21
TX	-5	-20	13	-43	-84	-652	0.03	-0.09	-0.17	-1.33
UT	-6	-20	16	14	-38	-358	0.04	0.03	-0.10	-0.90
VT	-3	-9	-14	-217	28	36	-0.03	-0.43	0.06	0.07
VA	-6	-21	1	-112	126	657	0.00	-0.20	0.23	1.20
WA	-4	-20	-39	-351	7	-76	-0.08	-0.70	0.01	-0.15
WV	-8	-54	175	1122	-84	-546	0.47	3.04	-0.23	-1.48
WI	-6	-22	10	-35	-16	-226	0.02	-0.07	-0.03	-0.46
WY	-7	-43	384	2512	-214	-1365	0.87	5.71	-0.49	-3.10
U.S.	-6	-25	-5	-151	-5	-229	-0.01	-0.29	-0.01	-0.44

Table 5 Decomposition of Welfare Effects from Bingaman-Domenici and Mc-Cain Lieberman Equivalent CO_2 Taxes

	1. Chg. in p.c. Factor Income		2. Chg. in p.c. Revenue Raised by State Taxes				3. Chg. in p.c. Revenue Raised by Federal Taxes			
	State Recycling ($)		State Recycling ($)		Federal Recycling ($)		State Recycling ($)		Federal Recycling ($)	
	BD	MCL	BD	MCL	BD	MCL	BD	MCL	BD	MCL
AL	-168	-1146	252	1604	-9	-72	-33	-225	166	1037
AK	-422	-2915	695	4374	-51	-327	-62	-435	183	1094
AZ	-152	-1085	144	944	-2	-8	-24	-167	145	906
AR	-137	-965	195	274	-7	-46	-29	-198	140	869
CA	-128	-908	87	560	-2	-6	-17	-123	125	785
CO	-162	-1154	145	955	-2	-2	-20	-139	140	876
CT	-147	-1046	133	892	4	48	-18	-123	170	1076
DE	-132	-957	169	1116	1	21	-19	-132	143	898
DC	-48	-439	130	887	12	112	-53	-367	519	3288
FL	-145	-1029	130	834	-2	-7	-23	-165	145	904
GA	-132	-944	149	949	-3	-19	-21	-147	134	836
HI	-93	-682	118	771	-3	-13	-30	-211	164	1016
ID	-114	-826	121	795	-1	-1	-19	-136	129	806
IL	-146	-1010	155	995	-2	-6	-19	-137	139	870
IN	-220	-1468	337	2090	-15	-144	-23	-158	131	816
IA	-190	-1330	278	1794	-10	-84	-22	-153	145	906
KS	-157	-1093	195	1262	-7	-47	-25	-169	140	879
KY	-200	-1240	310	1863	-17	-176	-31	-210	160	999
LA	-197	-1384	309	1932	-11	-65	-44	-305	136	821
ME	-141	-1100	166	1088	-4	-26	-18	-129	178	1127
MD	-120	-887	129	846	-2	-9	-34	-238	284	1795
MA	-138	-1013	119	791	2	25	-19	-136	184	1167
MI	-131	-930	149	957	-3	-12	-22	-151	138	861
MN	-160	-1146	153	999	-5	-26	-19	-132	127	798
MS	-175	-1192	297	1837	-13	-114	-47	-321	157	960
MO	-152	-1046	207	1329	-8	-69	-27	-186	167	1044
MT	-167	-1151	246	1593	-11	-64	-38	-258	147	909
NE	-160	-1097	245	1566	-11	-95	-27	-183	143	898
NV	-243	-1721	236	1506	-1	3	-22	-152	109	674
NH	-146	-1083	146	958	4	35	-14	-95	145	919
NJ	-161	-1153	140	922	0	10	-19	-135	156	983
NM	-133	-926	214	1385	-11	-66	-42	-281	169	1048
NY	-141	-1049	131	858	0	8	-18	-126	172	1087
NC	-123	-891	152	971	-4	-24	-19	-132	138	867
ND	-391	-2011	630	3938	-38	-371	-50	-332	187	1160
OH	-135	-957	164	1042	-4	-24	-22	-156	144	901
OK	-167	-1159	207	1331	-6	-48	-34	-234	152	938
OR	-130	-923	122	803	-1	5	-18	-127	118	737
PA	-150	-1052	177	1146	1	18	-23	-162	177	1114
RI	-109	-819	100	663	1	9	-23	-161	202	1278
SC	-126	-888	182	1195	0	15	-25	-172	148	927
SD	-140	-1014	164	1070	0	7	-28	-198	173	1078
TN	-146	-983	181	1151	-6	-63	-24	-166	151	945
TX	-208	-1457	245	1553	0	14	-26	-179	122	752
UT	-140	-995	175	1139	-6	-35	-19	-131	107	670
VT	-131	-992	132	871	2	19	-15	-104	158	1001
VA	-126	-928	161	1053	-4	-25	-33	-231	257	1616
WA	-133	-958	117	770	0	10	-21	-151	141	884
WV	-239	-1453	456	2839	-21	-202	-42	-277	176	1097
WI	-139	-997	166	1085	-6	-38	-18	-126	128	805
WY	-324	-2048	745	4779	-20	-153	-38	-250	130	806
U.S.	-152	-1070	170	1082	-3	-20	-23	-163	150	940

References

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

Babiker, M. H., Metcalf, G. E. and Reilly, J. M. (2003). Tax distortions and global climate policy, *Journal of Environmental Economics and Management* **46**: 269–287.

Babiker, M., Reilly, J. M. and Jacoby, H. D. (2000). The Kyoto protocol and developing countries, *Energy Policy* **28**: 525–536.

Balistreri, E. J., McDaniel, C. A. and Wong, E. V. (2003). An estimation of U.S. industry-level capital-labor substitution elasticities: Support for Cobb-Douglas, *North American Journal of Economics and Finance* **14**(3): 343–356.

Balistreri, E. J. and 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. and 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, *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.

Böhringer, C. and Rutherford, T. F. (2002). Carbon abatement and international spillovers, *Environmental and Resource Economics* **22**: 391–417.

Bovenberg, A. L. and Goulder, L. H. (1996). Optimal environmental taxation in the presence of other taxes: General equilibrium analyses, *American Economic Review* **86**(4): 985–1000.

Brooke, A., Kendrick, D., Meeraus, A. and Raman, R. (1998). *GAMS: A User's Guide*, GAMS Development Corp., Washington DC.

Dirkse, S. P. and 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). State energy data 2000: Consumption, technical notes, *Technical report*, U.S. Department of Energy, Washington, D.C.

DOE/EIA (2003b). State energy data report, *Technical report*, U.S. Department of Energy, Washington, D.C.

DOE/EIA (2006). Annual energy outlook 2006 with projections to 2030, *DOE/EIA-0383(2006)*, U.S. Department of Energy, Washington, D.C.

Goulder, L. H., Parry, I. W. H. and Burtraw, D. (1997). Revenue-raising versus other approaches to environmental protection: The critical significance of preexisting tax distortions, *Rand Journal of Economics* **28**: 708–731.

IRS (2001). *Internal Revenue Service Data Book 2000, Publication 55B*, Internal Revenue Service, Washington, D.C.

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

Jackson, R. W., Schwarm, W. R., Okuyama, Y. and Islam, S. (2004). A method for constructing commodity by industry flow matrices, *Research Paper 2004-5*, Regional Research Institute, Morgantown, W.V.

Jacoby, H. D. and Reiner, D. M. (2001). Getting climate policy on track after the Hague, *International Affairs* **77**(2): 297–312.

Jorgenson, D. W., Goettle, R. J., Wilcoxen, P. J. and Ho, M. S. (2000). The role of substitution in understanding the costs of climate policy, *Report*, Pew Center on Global Climate Change.

Li, P.-C. and 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, *Finanzarchiv* **30**: 432–453.

Oladosu, G. and Rose, A. Z. (In Press). Income distribution impacts of climate change mitigation policy in the Susquehanna River Basin economy, *Energy Economics* .

Paltsev, S., Reilly, J. M., Jacoby, H. D., Ellerman, A. D. and Tay, K. H. (2003). Emissions trading to reduce greenhouse gas emissions in the United States: The McCain-Lieberman proposal, *Report No. 97*, MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA.

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

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

Reilly, J. M., Prinn, R. G., Harnisch, J., Fitzmaurice, J. M., Jacoby, H. D., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A. and Wang, C. (1999). Multi-gas assessment of the Kyoto Protocol, *Nature* **401**: 549–555.

Rose, A. Z. and 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. (2005). Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) model, *Working paper 05-01*, Research Triangle Institute.

Ross, M. T., Beach, R. H. and 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.

Rutherford, T. F. (1999). Applied general equilibrium modeling with MPSGE as a GAMS subsystem: an overview of the modeling framework and syntax, *Com-*

putational Economics **14**: 1–46.

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 U.S. CO_2 emissions, *Energy Policy* **in press**.

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

Sue Wing, I. and Eckaus, R. S. (2006). The decline in U.S. energy intensity: Its origins and implications for long-run CO_2 emission projections, *Energy Policy* **in press**.

Weyant, J. P. (1999). The costs of the Kyoto protocol: a multi-model evaluation, *Energy Journal* **Special Issue**.