The Regional Incidence of a National Greenhouse Gas Emission Limit: Title VII of the American Clean Energy and Security Act

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Abstract

This paper employs an interregional computable general equilibrium model to analyze the macroeconomic costs of greenhouse gas emission reductions under Title VII of the American Clean Energy and Security Act of 2009 (H.R. 2454), and to elucidate how these economic impacts are distributed among producers and consumers at the state level. The overall costs are found to be modest due to the moderating effect of abundant cheap international emission offsets, while the distribution of abatement burdens is strongly progressive across households but mildly regressive across states.

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1. Introduction

Title VII of the American Clean Energy and Security Act of 2009 (H.R. 2454) has the distinction of being the first piece of draft legislation to be passed by the U.S. Congress which imposes binding limits on domestic emissions of greenhouse gases (GHGs). This paper analyzes the macroeconomic costs of this trajectory of abatement, and elucidates the distribution of these economic impacts amongst producers and consumers at the state level.

H.R. 2454 is the latest of several legislative proposals to limit the U.S. economy's aggregate GHG emissions. While the key feature of all of these policies is that their economic costs are likely to distributed unevenly among states and regions, the relevant geographic patterns and their precursors have yet to be systematically characterized.[1] The present study addresses this gap in the literature by constructing a interregional computable general equilibrium (ICGE) model of the U.S. economy which facilitates analysis of the incidence of an economy-wide cap-and-trade system for 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. The issue of distribution has long been a feature of the international negotiations on climate change, figuring prominently in the U.S. withdrawal from the Kyoto Protocol,[2] as well as the continuing difficulty of securing binding commitments from developed and developing countries alike to reduce emissions beyond the Kyoto targets.[3]

From a political economy standpoint, a natural prior is that the costs of abatement are concentrated in a small number of fossil fuel-intensive states, whose representatives have an incentive to veto the passage of legislation to limit aggregate emissions. The paper's results illustrate that although this story is consistent with the distribution of states' primary abatement burdens, the income effects of H.R. 2454's provisions for allocating grandfathered emission rights among different firms and households substantially moderates these welfare impacts. The macroeconomic costs of H.R. 2454 are found to be manageable, in large part because of the moderating effect of abundant supplies of cheap emission offsets purchased from overseas. However, while the burden of CO_2 abatement is progressive when households at different levels of income are taken into account, the incidence of the aggregate costs borne by states ends up being mildly *regressive*. This outcome highlights the challenges inherent in targeting the recipients of emission rights and the considerable uncertainities which beset modeling of these allocation mechanisms. It also suggests the need to modify the allowance distribution scheme to

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[1] Early modeling studies which focused on the regional distribution of the costs of GHG abatement are Balistreri and Rutherford (2004), Ross et al. (2004) and Rose and Zhang (2004), while more recent analysis by Burtraw et al. (2008) focuses on the electric power sector. Regional incidence at the household level is Hassett et al. (2009) and Grainger and Kolstad (2009). Section 4 of the paper undertakes a detailed examination of their methodology and results.
[2] See, e.g., Jacoby and Reiner (2001).
[3] Cooper, H. "Leaders Will Delay Deal on Climate Change", New York Times, November 15, 2009, p. 6.

lower the costs to hardest hit states, and thereby induce greater progressivity in the geographic distribution of abatement burdens.

The rest of the paper is organized as follows. Section 2 introduces the major provisions of Title VII of H.R. 2454, discusses their key features, and outlines the strategies employed to model their economic impacts. Section 3 provides a brief description of the numerical model, whose results are presented and discussed in Section 4. Section 5 concludes with a summary of key findings, and a discussion of caveats and directions for future research.

2. Spatial and Temporal Features of Title VII's Abatement, Offset and Allowance Provisions

Title VII of H.R. 2454 establishes a cap-and-trade program for reducing GHGs, which begins in 2012 by limiting emissions to 97% of their 2005 levels, followed by further cuts to 80% in 2020, 58% in 2030, and 17% in 2005. The sequence of annual targets in §721(e)(1) of the bill is shown by the first series in Figure 1, and would seem to be immediately binding—if applied to carbon dioxide (CO_2) alone, the cap would require abatement of 10-15% of the emissions projected by the EIA Annual Energy Outlook 2009 reference case (series 6). However, several factors end up substantially loosening this restriction. First, the cap applies to entities that emit only 66% of aggregate emissions in the short run and 85% in the long run (§721(e)(2)(A)), which implies an equivalent cap for the aggregate economy that is 30-50% higher than the §721(e)(1) target initially and 18% higher in the long run (series 2). Second, the fact that the analysis below does not project non-CO_2 GHGs, which make up 15% of base year emissions, leads us to approximate the CO2-only cap on emissions using the §721(e)(1) targets after 2016, which scales in the cap downward as in series 3. The resulting sequence of CO_2-only targets is initially only just binding on the economy.

An important element of Title VII is the ability for covered entities to purchase emission offsets which may be credited against their abatement obligations. Nominally, §722(d)(1)(A)of the bill restricts offset use in the aggregate to 2 GT, no more than 1 GT of which may come from either domestic or international sources.[4] Series 4 indicates that this has the potential to substantially relax the cap, which with full offsets would only bind in 2027. However, a key subsidiary constraint on the operation of the foregoing provision is the pro-rating of covered entities' allowable offset use in year t by §722(d)(1)(B) according to the formula

$$\text{Percentage Offset Limit}_t = \frac{2000}{2000+\text{Cap}_{t-1}}.$$

where Cap_{t-1} denotes the preceding year's aggregate cap in $MTCO_2$ emissions. When this formula is applied to series 4, covered entities are able to offset a quarter of their abatement in the early years of the program, a figure which rises to 66% by 2050. The corresponding relaxation of the cap is shown in series 5, which indicates that although the pro-rating of offset credits does attenuate their use, the date at which the aggregate cap binds nonetheless remains significantly delayed. The final influence on offset use is §722(d)(1)(C), which in the event that fewer than 0.9 GT of domestic offsets are supplied gives the

[4] International offsets face a 25% discount upon surrender.

EPA administrator the discretion to relax the aggregate limit on covered entities' use of international offsets by up to 500 MT, and make the corresponding reduction in allowable domestic offset use. Consequently, the precise extent of relaxation of the cap cannot be predicted without a projection of allowance prices in conjunction with domestic and international offset supply schedules, but is likely to lie between series 2 and 4.

Availability of the approximately 1.5 GT of allowable offsets at prices lower than the marginal cost of the bulk of domestic abatement options can therefore postpone the onset of significant domestic emission reductions until well after 2020. The likelihood of this occurring depends on the banking and borrowing of allowances allowed under §725 of the bill. Banking in particular creates incentives for covered entities to undertake early actions to both abate emissions and purchase offset credits. Programmatic restrictions aside, the fundamental determinant of the relative attractiveness of these two compliance options is the price elasticity of offset supplies, especially in the early years of the policy. EIA (2009) and analyses by EPA assume that neither domestic nor international offset suppliers ramp up quickly enough that the 2 GT limit binds, and undertake scenario analysis to explore the impact of different assumptions about what level of supply will come in on what time frame. We follow in these studies' footsteps by developing supply functions based on estimates developed by EPA on the marginal cost of domestic and international GHG abatement in agriculture, forestry and land-use change and the demand for offsets by signatories to the Kyoto Protocol. Figure 2 illustrates the resulting residual supply schedules as a function of the allowance price (τ). Notwithstanding the considerable uncertainty in these projections, they suggest that the availability of offsets from domestic sources is likely to be an order of magnitude smaller than that from international sources, which in the first decade of the program are capable of satisfying the full 2GT annual limit at prices below \$20/ton CO_2. Moreover, over this same period domestic offset supplies become inelastic at 0.5-0.8 MT, making it very likely that lower-cost international credits will play an expanded role under the terms of the modified limit §722(d)(1)(C).

The final relevant feature of Title VII is the grandfathering of allowances, which plays a critical role in determining how the ultimate costs of the cap are distributed among U.S. states. The recipients of grandfathered allowances and their proportions of the total cap in 2012, 2016, 2030 and 2050 are described in great detail in §782-§795 of the bill, and are summarized in Table 1. The challenge which this allocation presents for modeling stems from the fact that in the logic of general equilibrium, households—not firms—own the factors of production, which in the present setting include emission rights. Therefore, for a given nominal allocation assumptions need to be made about the manner in which the value of the corresponding allowances accrues to shareholders, workers and consumers across states and households with different incomes. Accounting for the first two categories is problematic, as there is a dearth of information on the way in which the returns to capital and labor in a particular industry operating in a particular state are distributed, either across different states or among households of different income levels.[5]

[5] The capital (and, to a lesser extent, labor) earnings of a firm in a particular industry operating in one state are dispersed among households at different levels of income across *all* states. But no practical means exists to account for or model this, because of the paucity of data on interstate income transfers (see, generally, Kalemli-

Our assumptions in this regard are outlined in Table 2. For the categories that explicitly target the consumers of various industries (electricity load distribution companies (LDCs), small electric LDC energy efficiency programs, natural gas LDCs, home heating oil consumers, and state efficiency and renewable programs) the allocation process in modeled in two steps. The designated share of allowances is first distributed across states according to economic characteristics which mirror the provisions of the bill. Then the resulting allocations in each state are distributed among its constituent households. For the remaining allocation categories the distribution of allowances is made in a one-shot fashion. Allowances set aside for low and moderate income consumers were distributed among the poorest three household income classes according to their shares of population. It was assumed that the value of allowances designated for energy intensive industries and supplemental agricultural incentives would be captured by the consumers of goods produced by these sectors. Accordingly, their allocation was based on the state × household shares of consumption of each of these goods. The value of allowances set aside for worker adjustment assistance and training was assumed to be captured by labor, which we modeled by distributing these permits according to the state × household shares of national labor income. Several allocation categories set aside permits for industries (merchant coal-fired electricity generators, long-term contract generators, carbon capture and sequestration, clean cars, oil refineries). It was assumed that the value of these allowances would be captured by the shareholders of the industries in question, and the permits were distributed in proportion to the state × household shares of national capital income. Finally, it was assumed that allowances in the remaining categories, as well as those not specifically designated in the text of the bill, were distributed according to the state × household shares of national population.

These calculations were made for the five benchmark years, generating allocations were summed over categories to give the aggregate state × household distribution of allowances. Our final step was to interpolate the latter for the periods between benchmark years. The resulting distributions of allowances are summarized in Figure 3. Panel A indicates that across states the allocation mechanism favors more populous states such as California, Texas, New York, Florida, Illinois and Pennsylvania. The spread of allowances across households by income in panel B is less straightforward, consisting of a bell-shaped income distribution whose lower tail is shifted upward. To facilitate intuition, Figure 4 shows a hypothetical allocation made up of 50% of allowances distributed on the basis of population, 15% of allowances distributed to the lowest three income groups on the basis of their population, and the remaining percentage distributed based on households' labor and capital earnings. The striking similarity between the resulting distribution and Figure 3B indicates the importance of Title VII's for low-income allocation provisions for the overall distribution of allowances—and, as we shall see, economic impact.

Ozcan et al., 2008) and the confidential nature of this information at any but the coarsest level of sectoral aggregation.

3. Modeling

The analytical tool employed to simulate the economic impacts of Title VII is an inter-regional computable general equilibrium (ICGE) model, calibrated to IMPLAN state social accounting matrices (Minnesota IMPLAN Group, 2008) using tools developed by Rausch and Rutherford (2008). The ICGE model is a dynamic variant of the static model developed by Sue Wing (2007, 2008) which solves for the prices and quantities across multiple markets in the U.S. economy as a sequence of equilibria over the period 2007-2050 with a one-year time-step. It resolves ten industry sectors (the three fossil fuel sectors, 2 non-fossil energy sectors and 5 non-energy sectors shown in panel A of Figure 5), nine household income groupings and three types of government activity within the 50 states and the District of Columbia. The households which make up each income category are modeled as a representative agent with constant elasticity of substitution (CES) preferences and a constant marginal propensity to save out of income. As illustrated in panel B of Figure 5, each industry is modeled as a representative firm which produces a single commodity for in-state and out-of-state markets according to a nested CES production technology. Interstate trade in commodities is modeled using the Armington assumption, in which every state's use of a good is a CES composite of in-state and out-of-state varieties.

Households' endowments of capital make up an aggregate pool of capital services which is then allocated among sectors and states to yield a single rate of return. Simultaneously, however, the model's one-year time-step is too short a period for inter-sectoral differences in rental rates to be arbitraged by movements of capital among states and industries. Unlike models with a longer time-step, which utilize a vintage capital specification (e.g., Jacoby and Sue Wing, 1999) or simply treat extant capital as being frictionlessly reallocated (e.g., Sue Wing and Eckaus, 2007), we adopt a hybrid approach which treats capital as being subject to sluggish contemporaneous reallocation. We do this by modeling sectoral capital demands as a constant elasticity of transformation (CET) function of the aggregate capital supply with an elasticity of 0.1. The resulting structure is sufficiently rigid that the emission limit does not substantially alter the intra-period allocation of extant capital, and generates sector $\times$ state rental rate differentials that are arbitraged over subsequent periods by the allocation of investment. Short-run labor market frictions are modeled in a similar manner. Households' labor endowments are combined into state-level pools which are then allocated locally among industries. Intersectoral labor movements are assumed to occur on a time-frame longer than the model's time-step, and the consequent sluggish reallocation is modeled by specifying sectoral labor demands in each state as a CET function of the corresponding state's supply with an elasticity of 0.5. The larger elasticity allows for greater reallocation of labor as compared to capital. The static equilibrium sub-model is numerically calibrated and formulated as a large-scale mixed complementarity problem using the MPSGE subsystem (Rutherford, 1999) for GAMS (Brooke et al., 1998), and is solved using the PATH solver (Ferris et al., 2002).

The model steps through time by updating four sets of variables at the state level:

- Endowments of labor, based on projections of state population growth from the Census.
- Endowments of capital input as a result of accumulation of sectoral capital stocks in each state, each of which is modeled according to the standard perpetual inventory assumption. Investment funds are assumed to be allocated to the activities earning the highest rates of return, which we model by

allocating the aggregate pool of investment at each time-step among industries and states in proportion to their shares of aggregate payments to capital.[6] Households' capital endowments are updated by applying the benchmark distribution of capital ownership among income classes to the one-period-ahead aggregate value of industries' capital stocks.

- Region-specific rates of improvement in the productivity of labor, modeled by exogenously-specified, declining trends in the coefficient on labor in the sectoral production functions.
- Region-specific rates of autonomous energy efficiency improvement (AEEI), represented by exogenously declining trends in the coefficients on energy in producers' cost and consumers' expenditure functions.

The growth rates of labor productivity and AEEI were adjusted so that the model's business-as-usual (BAU) solution roughly matched the trends in the Annual Energy Outlook (AEO) 2009 projections of emissions, GDP and regional income.[7]

CO_2 emissions are modeled by applying constant emission factors to producers' and consumers' demands for energy commodities.[8] The current version of the model does not resolve emissions of non-CO_2 GHGs, which made it necessary to represent H.R. 2454's targets in terms of equivalent limits on CO_2.[9] As mentioned above, this was done by using the adjusted target in series 3 of Figure 1 to approximate an aggregate CO_2-only cap. The supply functions for domestic and international offsets were introduced into the model as auxiliary constraints on the intra-period equilibrium problem, and generate price-endogenous endowments of emission rights that supplement the allocations discussed

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[6] At each time-step t, savings in household h and state s are determined by the savings rate, $\varrho_{h,s}$, and income$M_{h,s,t}$. Savings are assumed to equal investment, whose aggregate quantity is given by $\mathcal{I}_t = \sum_h \sum_s \varrho_{h,s} M_{h,s,t}$. We allocate this pool of funds among states and industries in proportion to the instantaneous return to capital, $v^K_{j,s,t}$, which pins down sectoral investment as $I_{j,s,t} = \sum_j \sum_s \psi^K_{j,s,t} \mathcal{I}_t$, with $\psi^K_{j,s,t} = v^K_{j,s,t} / \sum_j \sum_s v^K_{j,s,t}$ indicating each sector's share of aggregate capital earnings. Sectoral capital stocks are then updated using the perpetual inventory formula: $K_{j,s,t+1} = I_{j,s,t} + (1-\delta)K_{j,s,t}$, in which δ indicates the rate of capital depreciation. We use the one-period-ahead capital stock to compute the succeeding period's endowment of capital input, using the assumption that the aggregate portfolio of sectoral returns to capital accrues to households in proportion to their saving. Then, using r to denote the aggregate rate of return, we have:

$$V^K_{h,s,t+1} = \left(\frac{\varrho_{h,s} M_{h,s,t}}{\sum_h \sum_s \varrho_{h,s} M_{h,s,t}}\right)(r+\delta) \sum_j \sum_s \left(K_{j,s,t+1} - K_{j,s,t}\right) + V^K_{h,s,t}.$$

[7] Over the period 2007-2030, trends in regional income produced by the model were broadly consistent with those in the AEO. Emissions and GDP generated by the model were somewhat higher, however. In particular, the growth rate of AEEI necessary to bring projected CO_2 emissions in line with the AEO substantially exceeded historically-observed rates of decline in energy intensity at the state level.

[8] The relevant coefficients were constructed by distributing AEO 2009 CO_2 emissions by sector and fuel for the 2007 benchmark year among states and dividing the result by the economic value of energy inputs in the IMPLAN SAMs.

[9] Non-CO_2 GHGs make up 15% of emissions in the 2007 base year (EPA, 2009), which suggests that the model's baseline emission trajectory is biased downward, underestimating H.R. 2454's macroeconomic cost. There is also a bias in the opposite direction which derives from the model's omission of non-CO_2 GHGs' lower cost of abatement, especially in the near term (Hyman et al, 2003). The ultimate cost savings that result depend on non-CO_2 GHGs' abatement potential, which EPA (2006) estimates might be as much as 300 MT annually at $10/ton in 2020. Precisely what the balance of these forces implies for the cost of H.R. 2454 depends crucially on the baseline trajectories of the states' non-CO_2 GHG emissions, modeling of which awaits comprehensive data on states non-CO_2 GHG emissions. The development of these data lies well beyond the scope of the present study.

above. It was assumed that offsets would be purchased by firms, and primarily financed by their shareholders. This was represented in the model by distributing the aggregate quantity of offset credits among states and households in proportion to their shares of aggregate capital earnings. To account consistently for international offsets as an import good, their supplies were balanced by countervailing outward transfers of funds from the households and states where these purchases were made. The same was done for the three categories of allowances whose auction revenue is to be transferred abroad (international adaptation, international clean technology transfer, and supplemental reductions).

The total allocation of allowances, net of offset purchases, were designated as an upper bound on the CO_2 content of the fossil fuels used in the model's simulated activities. Specifying a single shadow price that exhibits complementary slackness with respect to these various state-level constraints forces the model to compute the implicit CO_2 tax dual to the aggregate emission cap, which in general equilibrium is synonymous with the market-clearing price of allowances.[10] Banking was modeled using an iterative scheme which draws on the key theoretical result that the competitive equilibrium of an intertemporal tradable permit market generates an allowance price trajectory which rises at the rate of discount (see, e.g., Kling and Rubin, 1997). Using a discount rate of 7.4% (consistent with EIA, 2009), an initial permit price was specified in the 2012 period which then determined the path to 2050. The resulting cumulative emissions were then compared against allowable cumulative emissions under the cap in Figure 1, the initial price was adjusted, and the model was simulated again until the actual cumulative emissions exceeded the allowable quantity by no more than 1%.

4. Results

The economy's aggregate response to Title VII is summarized in Figure 6. BAU emissions rise at an average annual growth rate of half of one percent, exceeding 7.4 GT in 2050. The imposition of the cap with banking precipitates an immediate one-time emissions reduction of 760 MT in 2012, followed by an increase in abatement averaging 3.5% per annum thereafter. Allowance prices, which start out at $7/ton CO_2 in 2012 and increase to$12/ton in 2020 and $105/ton in 2050, are moderated by a large influx of offsets which relaxes the cap by an average of 1.4 GT per year. The joint implications of Title VII's banking and offset limitation provisions are illustrated by re-running the model assuming year-by-year compliance with the cap. Under these conditions few offsets end up being purchased in the early years when the cap is lightly binding and allowance prices are low. But after 2020, offset purchases increase with the permit price until they hit the §722(d)(1) ceiling in 2030, after which the trajectory of their demand is the same as that of the banking scenario in spite of the fact that allowance prices are much higher.

Figure 7 more clearly illustrates the extent of early action induced by banking, and the importance of offsets as a compliance mechanism. Panel A suggests that in 2012 abatement alone is likely to be more than four times what is required by the cap, and purchases of offset credits are one and a half times as

[10] A key consequence is that in any given year, the resulting constrained allocation of fossil fuel use and associated emissions is largely invariant to the interstate distribution of allowances, while the geographic distribution of welfare impacts is not.

large as emission reductions. Emission reductions from the BAU warranted by the cap catch up with real abatement only in 2019, and surpass all compliance measures in 2031. Consistent with the discussion of offsets above, the relatively high cost and limited technical potential of domestic offsets are assumed to trigger §722(d)(1)(C), which clears the way for international sources to supply the overwhelming majority of offset credits. Domestic offsets supplies start out at 122 MT and peak at 504MT in 2042, while the largest use of international offsets is made initially, in the amount of 1.25 GT, and subsequently declines by one third over the course of the simulation. The relative importance of offsets wanes over time, with the quantity of real abatement surpassing offset purchases by 2023 and growing to outweigh offsets by more than three to one in 2050. Panel B illustrates that early over-compliance leads to the accumulation of a substantial bank of emission credits which peaks at 21 GT in 2030. The lion's share of these credits is generated by Northeastern and Western states (40% and 35%, respectively) which retain positive balances through the end of the simulation horizon, while states in the Midwest and the South run short of credits by 2045, after which they purchaser emission rights from the rest of the country.

The underlying patterns of regional adjustment are summarized in Figure 8. Panel A plots regions' abatement responses to allowance prices along the economy's counterfactual trajectory. These indicate that abatement opportunities are concentrated in states in the Midwest and, to a lesser extent, the South. By 2050, Title VII reduces aggregate U.S. emissions by 46% below BAU levels, accomplished through reductions of similar in magnitude in Southern states, large reductions in the Midwest (54%), and smaller reductions in the West (40%) and the Northeast (37%). Panel B indicates that BAU emissions and abatement are both dominated by the fast-growing, high-emitting South—and to a lesser extent the Midwest. Northeastern states' low initial emission intensity and stable population causes them to play only a minor role in terms of both baseline CO_2 and emission reductions. Western states' larger economies and higher emissions are offset by their limited abatement possibilities, which prevent them from achieving substantial emission reductions.

Table 3 sheds light on the state-level detail behind these results in the year 2020. Panel A indicates that BAU emissions are dominated by Texas, and to a lesser extent California, Illinois and Florida. The geographic distribution of allowances in Panel B is broadly consistent with the implications of the allocation analysis in section 1. Panel C shows that by 2020 the Title VII target is a binding constraint on emissions in four-fifths of the states, with remainder holding excess permits (so called "hot air") located primarily in New England and California. Panel D indicates that more than half of the states continue to emit more than their allocation, with deficits in Georgia, Louisiana and particularly Texas leading to an aggregate net deficit of 43MT. Although the latter is more than covered by current purchases of offsets, the allocation of allowances nonetheless has important ramifications for income distribution. The three "short" states identified above collectively spend $3.8 billion on allowance purchases, while California and Mid-Atlantic states that emit less than their allocation together receive $4.6 billion from sales of excess permits, and the U.S. as a whole transfers $15 billion abroad to purchase international offsets.

The impacts of Title VII on states' economies in 2020 are shown in Table 4. Panel A shows that real GDP falls relative to its baseline level in all states, but the corresponding losses are generally small—0.5% or less for three quarters of states. The 0.4% average reduction in aggregate GDP is slightly higher than that projected by EIA. Nevertheless, the three coal-intensive states of Wyoming, West Virginia and Kentucky, incur losses in excess of 0.75%. The attendant reductions in real income shown in panel B are similar but generally smaller, with annual losses in hardest-hit states more than double the nationwide average of -0.33%, or $170 per person. Panel C sheds light on the consequences for welfare, measured as the fraction of benchmark consumption foregone as a result of changes in goods prices and reductions in income. In contrast to GDP or personal income, Title VII's induces increased expenditure on consumption in 60% of states, with a national average effect that is slightly positive and follows a similar interstate distribution. In general, energy-producing (especially coal) states incur the largest losses—which are themselves relatively small, while at the opposite end of the spectrum states such as Vermont and the Dakotas see substantial *increases* in consumption.

Overall, these results suggest that the welfare impact of the reduction in aggregate income is cushioned by a contemporaneous increase in consumption. However, the latter occurs at the expense of investment, which over time lowers the economy's aggregate rate of capital accumulation, and, ultimately, growth. The magnitude of these effects is small in aggregate terms: by 2050 Title VII lowers real GDP by 1.5% compared to the baseline scenario, which is equivalent to shaving one tenth of one percent off of the long-run average annual rate of economic growth.

Figure 9 illustrates the considerable heterogeneity in the cap's influence on the consumer price of energy commodities. Bearing in mind the caveat that the price changes in each state are an artifact of the model's simplified Armington trade structure, several broad patterns nonetheless emerge.[11] Consistent with other CGE studies of climate policy, the price of coal rises substantially, with increases of up to 350%, while the potential for emission-free generation to substitute for fossil fuels in the electric power sector sharply attenuates the increase in the electricity price, which ranges from 1-8%. There is greater interstate heterogeneity in the price of natural gas as compared to petroleum, with most states seeing a 4-10% increase in the former, and a 5-25% increase in the latter. These ranges are all somewhat larger than those found by EIA for the same year. Title VII's effects on the consumer prices of other commodities are much smaller, with increases in the prices of transportation and energy-intensive goods averaging 0.4% and 0.1%, and declines in the prices of services and manufactures averaging 0.3% and 0.1%.

This last result highlights the importance of a general equilibrium approach to capturing the implications of price changes for income and substitution effects across industries and states. Recent estimates of the burden of climate policy by Hassett et al. (2009) and Grainger and Kolstad (2009) (hereafter HMM and GK) consider only the supply side of the economy in determining the effect of a carbon tax on commodity prices, and, assume that producers and consumers are not capable of engaging in substitution. A particular consequence of these assumptions is that the tax increases the prices of all commodities without exception, which the present results show is unlikely. Moreover, HMM's and GK's estimates of the burden of the tax are premised on consumers behaving as though they continue to purchase the same quantity of all goods in spite of higher prices. To illustrate the implications of this

[11] It is likely that "bottom-up" engineering models which incorporate the details of energy supply networks and a broader array of discrete energy conversion technologies will generate different patterns of interstate impacts.

assumption we go on to compute the HMM/GK measure of burden and compare it to the true change in expenditure computed by the model.[12]

The results, summarized in Table 4, break down the incidence households in different income categories by geographic region. Our general equilibrium analogue of the HMM/GK direct burden (the change in expenditure with fixed consumption due to the change in energy prices) is uniformly positive and small, varying between 0.16% and 0.25% of income, while the indirect burden (the corresponding change in expenditure due to the change in the price of non-energy goods) is *negative* and about two-thirds as large. The key to the second outcome is the decline in the price of services, which is a commodity that makes up a large share of household expenditure (75% on average). The resulting overall burden is slight, uniformly less than 0.15% of income, which suggests that the inability of producers and consumers to adjust through substitution in HMM/GK-type analyses is responsible for an upward bias in their estimates.

Panels A, B and C also reflect a crucial aspect of HMM's and GK's findings, namely that climate policy is regressive in its effect. The direct burden is largest in low to middle income households (those with incomes of $10-$35,000 in 2007), while the negative indirect burden is more or less uniformly spread across income classes, resulting in a distribution of total impact that mirrors the direct burden. Based on projections of average household income, this translates into negligible changes in annual expenditure: increases of $5 for households earning less than $10,000 and $21 for those earning $50-75,000 in 2007 and declines of $12 for households earning more than $150,000 in 2007).[13] Despite their small magnitude, these results highlight an important geographic dimension to the regressivity of policy costs, with direct and total burdens concentrated in the West Central and Mountain regions where per capita incomes are relatively low.

Nevertheless, we take pains to emphasize that the foregoing results should be interpreted with extreme care, as a very different picture emerges when adjustments in the quantity of consumption are taken into account. Panel D indicates that households in the three lowest income classes substantially increase the quantities of goods and services they consume, while households in the remaining income classes experience small declines in the quantity of their consumption. The result is that percentage reductions in real consumption expenditures tilt strongly toward the upper income brackets, indicating substantial progressivity. Even so, the underlying drivers are similar: real energy-related expenditures rise for all households, while real non-energy expenditures increase for households with 2007 incomes under $25,000 but decrease for the rest, leading to increases in consumption among the poor that are offset by declining consumption particularly in middle-income households. On average, households earning

[12] The expenditure of an individual who consumes quantities c_i of i commodities at initial prices $p_i$is $\sum_i p_i c_i$. The burden incurred by a change in prices to $p_i' > p_i$ is measured by HMM/GK as $\sum_i (p_i' - p_i) c_i$, which assumes a constant level of consumption. However, if consumption adjusts to c_i' as a consequence of income and substitution effects, the appropriate indicator of the welfare loss is the change in expenditure, $\sum_i (p_i' c_i' - p_i c_i)$. This is the measure reported in Tables 3.C and 4.D.

[13] It is important to realize that although our household income categories are initially defined in *today's* dollars, the resulting groups of individuals see their income, population and numbers of households grow over time. The income cutoffs in the header row of Table 4 should therefore be thought of as illustrative, as they have no bearing on the model's solution in non-benchmark years.

less than $10,000 in 2007 experience a real annual consumption gain of about $250, while those with base-year earnings of $35,000-$50,000 incur a loss of around $52, and those in the highest income bracket see a loss of only $7. Interestingly, the geographic distribution of consumption impacts is unchanged, with the gains concentrated in the New England, East-Central, Mid-Atlantic regions, and the largest losses occurring in South-Central and Mountain states.

Table 5 presents detailed welfare impacts for different households within each state, expressed in terms of the theoretically correct measure of percentage change in household utility from the BAU level (i.e., equivalent variation) computed by the model. These results are summarized in Figure 10, which plots the distribution of percentage equivalent variation within each household income class in panel A, and the interstate distribution of average welfare changes in panel B.[14] The extent of progressivity is evident from panel A: while the amplitude of the distribution of high- and middle-income households' losses does not exhibit much variation, the distribution of gains enjoyed by the poorest households has a longer tail and a median eight times as large in absolute terms as those with 2007 incomes of $35,000 and above. But an important caveat to this result is that in the hardest hit states (Wyoming and West Virginia) the losses experienced by middle-income households are 4-5 times the national average. Similarly, the pattern of interstate impacts in panel B illustrates the concentration of welfare losses in energy producing states, which occurs in spite of the fact that Title VII's allocation provisions generate substantial welfare improvements for the poorest households (increases in the real quantity of consumption of 1-3% everywhere except DC). It is noteworthy that the welfare losses in the figure tend to fall more heavily states with relatively low per capita incomes, which suggests that the incidence of Title VII is simultaneously progressive across income groups but regressive across states.

Our final step is to formalize this intuition by developing summary measures of the progressivity of the cap and trade scheme. The most widely used measure of the progressivity of a tax is the Suits Index (Suits, 1977), which is a Gini coefficient of the distribution of the burden of a tax with income. In the appendix we develop a modified Suits Index by constructing a Gini coefficient of the distribution of consumption expenditures foregone relative to their baseline levels, adjusting for the fact that a substantial fraction of households in different states see their consumption *rise*. (Details of the adjustment procedure are given in an appendix.) Figure 11 plots the corresponding Lorenz curves of changes in consumption, taking into account the distribution of welfare impacts across states and households in panel A, and states aggregating across households in panel B. The former is highly progressive, with a modified Suits Index of 0.56, while the latter is mildly regressive, with a modified Suits Index of -0.12.

This result indicates the difficulty of targeting grandfathered allowances in a way that enables the incidence of a cap-and-trade scheme to be progressive across both states and households at different levels of income. In particular, it appears that Title VII's allocation provisions do little to alleviate the burden on middle-income households (those with 2007 incomes of $35,000-$75,000) in the energy producing states which experience the largest declines in GDP and factor income. As a technical matter, this does not appear to be an insurmountable problem. A potential way of addressing it within the

[14] The latter is weighted by households' shares of each state's total consumption expenditure in the BAU scenario.

framework of the existing legislation might be to modify the provisions governing the allocation of allowances to workers (§782(k)) to more specifically target middle-income earners in energy producing states.

5. Summary, Caveats and Priorities for Future Research

The main conclusion of this study is that overall costs of the GHG emission limits under Title VII of H.R. 2454 are significant but manageable. The key to this result is the bill's generous provisions for covered entities to use offsets as a compliance mechanism, which ends up loosening the aggregate cap on emissions by as much as 1.4 GT annually, and accounts for 40% of the cumulative abatement to 2050 mandated by the bill. In the medium term (year 2020), the aggregate costs of abatement are less than 0.5% of GDP, which on average translates into annual losses of $69 worth of consumption expenditures. However, there is substantial heterogeneity in these burdens, among both states and household income levels. In contrast to recent studies, the overall burden of emission reductions was found to be progressive, with a large and positive impact on the poorest households, whose average consumption expenditures increase by $1042, at the same time as those of the richest households decline by $222 and those of middle-income households (those earning $50-75,000 in 2007) fall by $355. Notwithstanding this, the grandfathering of allowances and the use of offsets only partially mitigate the costs incurred by relatively poor energy—and particularly coal—producing states in the South and Mountain regions of the country, where consumers' overall percentage equivalent variation losses are more than ten times the national average.

These findings raise two critical issues. One relates to policy, specifically, whether the bill's allowance allocations provisions can be fine tuned to remedy the regressivity of abatement costs across states, and, if not, what additional measures might be necessary to moderate the burdens borne by fossil-fuel producing states—and especially middle-income households therein. The other relates to modeling. The results presented here are conditional on a host of assumptions, the most speculative of which arise in the translation of legislative language into mathematical formulas capable of capturing the ultimate ownership of allowances and the costs of purchasing offsets—both geographically and among households with different incomes.

The impact of different modeling assumptions in this regard can be tested through sensitivity analysis, with the goal of establishing the relative importance of allocation and transfers versus more fundamental economic forces on the distributional patterns generated by the model. Such an exercise is a prime candidate for future research, but fundamental gaps in our knowledge make it difficult to bound the space of alternatives. The key desideratum on the demand side is empirical evidence on the channels by which subsidies (a proxy for value of permit allocations) or taxes (a proxy for the costs of offset purchases) for firms in one state pass through to households at various levels of income in other states. The analogue on the supply-side is an understanding of the pace at which H.R. 2454 or similar policies might catalyze a ramp-up in developing countries' production of certified emission reduction (CER) credits. This is a key area of concern given offsets' pre-eminent cost-moderating role, the currently limited supply of CERs from the official Clean Development Mechanism project pipeline, and the potential for international offset suppliers to exercise market power.

Beyond these considerations, other caveats to the results hinge on elements of the ICGE model's structure, particularly its assumption of full employment, as well as its omission of non-CO_2 GHGs and backstop energy supply technologies. The inclusion of the payroll tax structure and labor-leisure choice by the representative agents is a priority for enhancing the veracity of the model, particularly given the potential for these elements to capture the as yet omitted welfare impacts of changes in the burden of pre-existing factor taxes on households' labor supply decisions. The bias associated with omission of emissions of high global-warming-potential gases has already been discussed, but the omission of backstop technologies is unlikely to be consequential. In light of the cost structure of advanced electricity supply technologies such as integrated coal-gasification with CO_2-capture and sequestration (CCS—McFarland et al., 2009) and renewables more generally (Sue Wing, 2006), it is doubtful that the present allowance price path will be sufficient to induce appreciable penetration of low-emission energy supplies before 2035. Modeling these sorts of technological details will be necessary if we want to include the additional economic impacts of Title I of H.R. 2454, which establishes a renewable electricity standard and mandates taxes on existing fossil electricity generation to finance CCS research, development and demonstration projects. In particular, the distortionary effects of forcing in larger quantities of more costly low-carbon electricity may well drive up allowance prices and abatement burdens, but evidence on this conjecture must await further model development and analysis.

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Figure 1. H.R. 2454 Emission Targets, Coverage and Offset Provisions

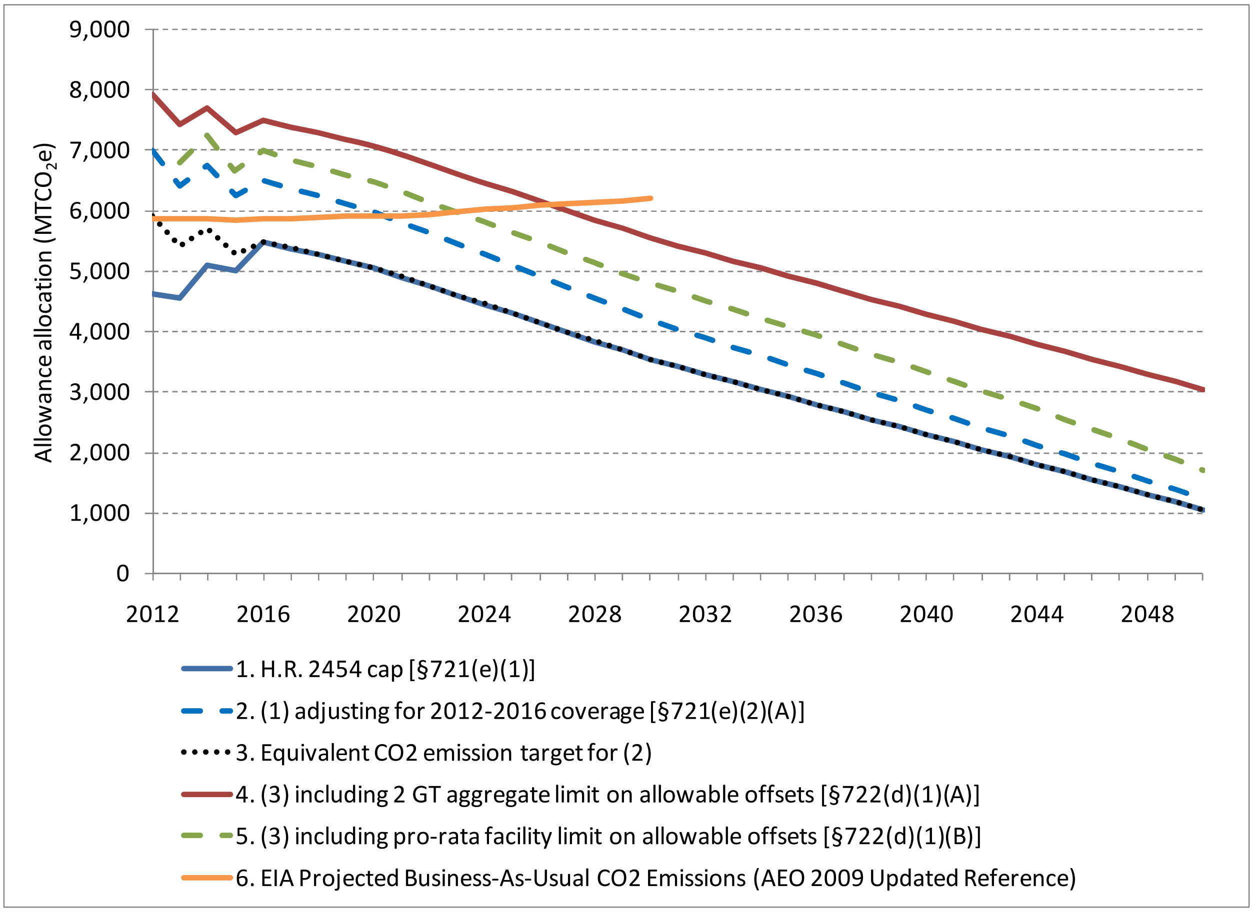
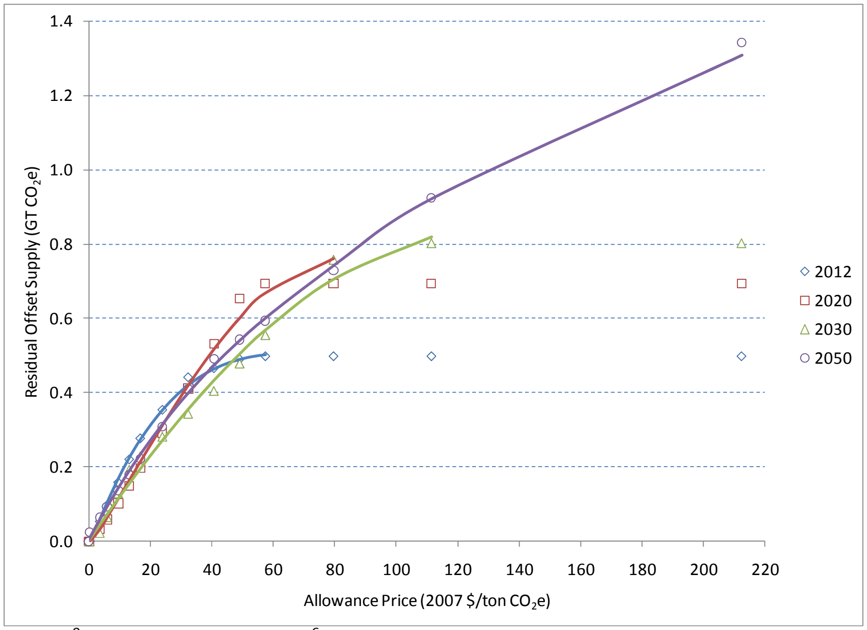
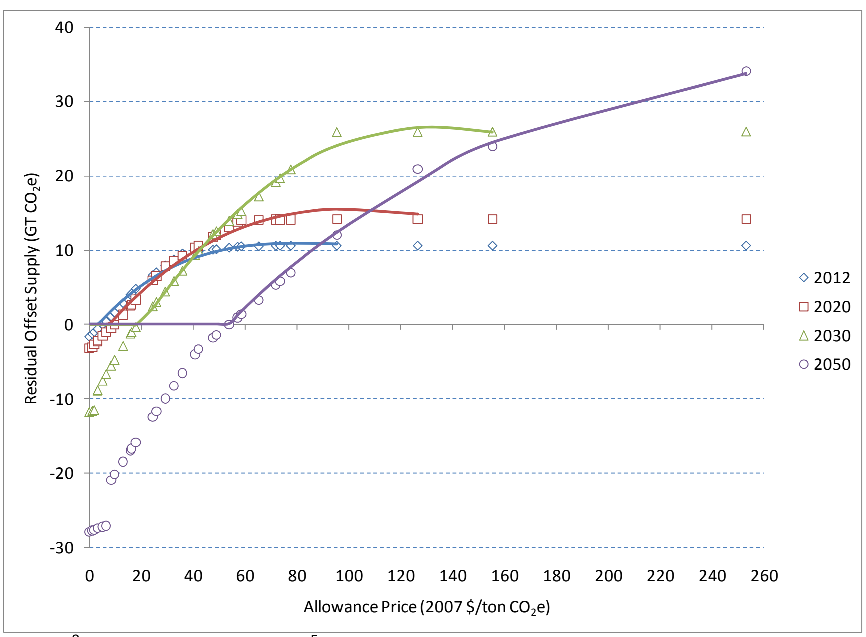


Figure 2. Residual U.S. Offset Supply Functions Calibrated to EPA Data



2012: Offsets = -5 x 10^{-9} max $(190, \tau)^4$ + 2 x 10^{-6} max $(190, \tau)^3$ – 0.0003 max $(190, \tau)^2$ + 0.0224 max $(190, \tau)$ – 0.0146
2020: Offsets = 6 x 10^{-9} max $(190, \tau)^4$ – 2 x 10^{-6} max $(190, \tau)^3$ + 6 x 10^{-5} max $(190, \tau)^2$ + 0.0133 max $(190, \tau)$ – 0.017
2030: Offsets = 7 x 10^{-10} max $(190, \tau)^4$ – 2 x 10^{-7} max $(190, \tau)^3$ – 3 x 10^{-5} max $(190, \tau)^2$ + 0.012 max $(190, \tau)$ + 0.0039
2050: Offsets = -2 x 10^{-9} max $(190, \tau)^4$ + 7 x 10^{-7} max $(190, \tau)^3$ – 0.0001 max $(190, \tau)^2$ + 0.0156 max $(190, \tau)$ + 0.005

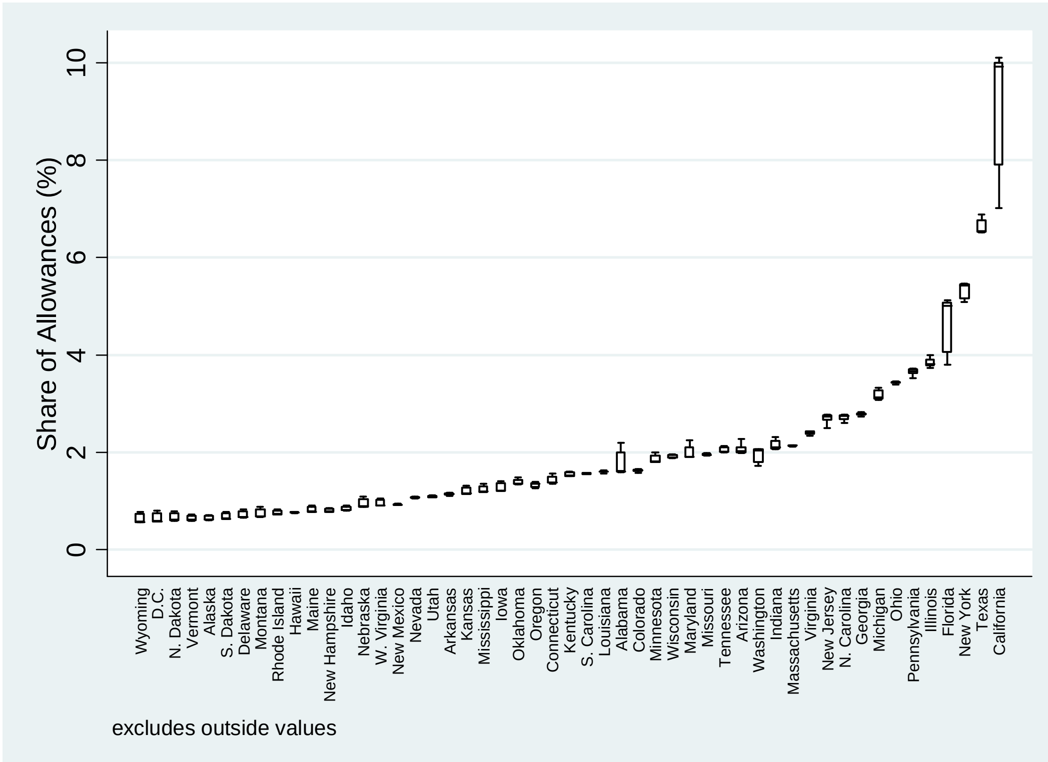
A. Domestic



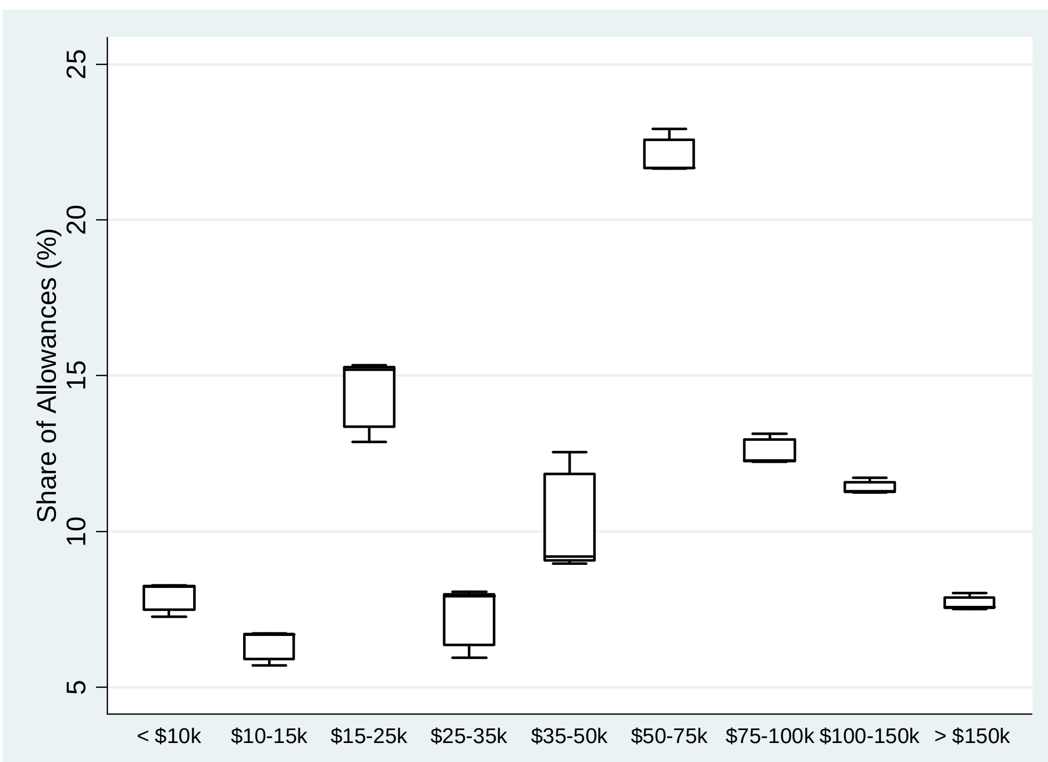
2012: Offsets = -4 x 10^{-8} max $(230, \tau)^4$ + 2 x 10^{-5} max $(230, \tau)^3$ – 0.0051 max $(230, \tau)^2$ + 0.4257 max $(230, \tau)$ – 1.4449
2020: Offsets = 2 x 10^{-9} max $(230, \tau)^4$ + 6 x 10^{-6} max $(230, \tau)^3$ – 0.0032 max $(230, \tau)^2$ + 0.4388 max $(230, \tau)$ – 3.1453
2030: Offsets = 3 x 10^{-8} max $(230, \tau)^4$ – 7 x 10^{-6} max $(230, \tau)^3$ – 0.0017 max $(230, \tau)^2$ + 0.5679 max $(230, \tau)$ – 10.556
2050: Offsets = -3 x 10^{-8} max $(230, \tau)^4$ + 2 x 10^{-5} max $(230, \tau)^3$ – 0.0044 max $(230, \tau)^2$ + 0.7071 max $(230, \tau)$ – 27.714

B. International

Figure 3. State and Household Distribution of Allowances, 2012-2050



A. Distribution across states



B. Distribution across household income groups

Figure 4. Hypothetical Allowance Allocation

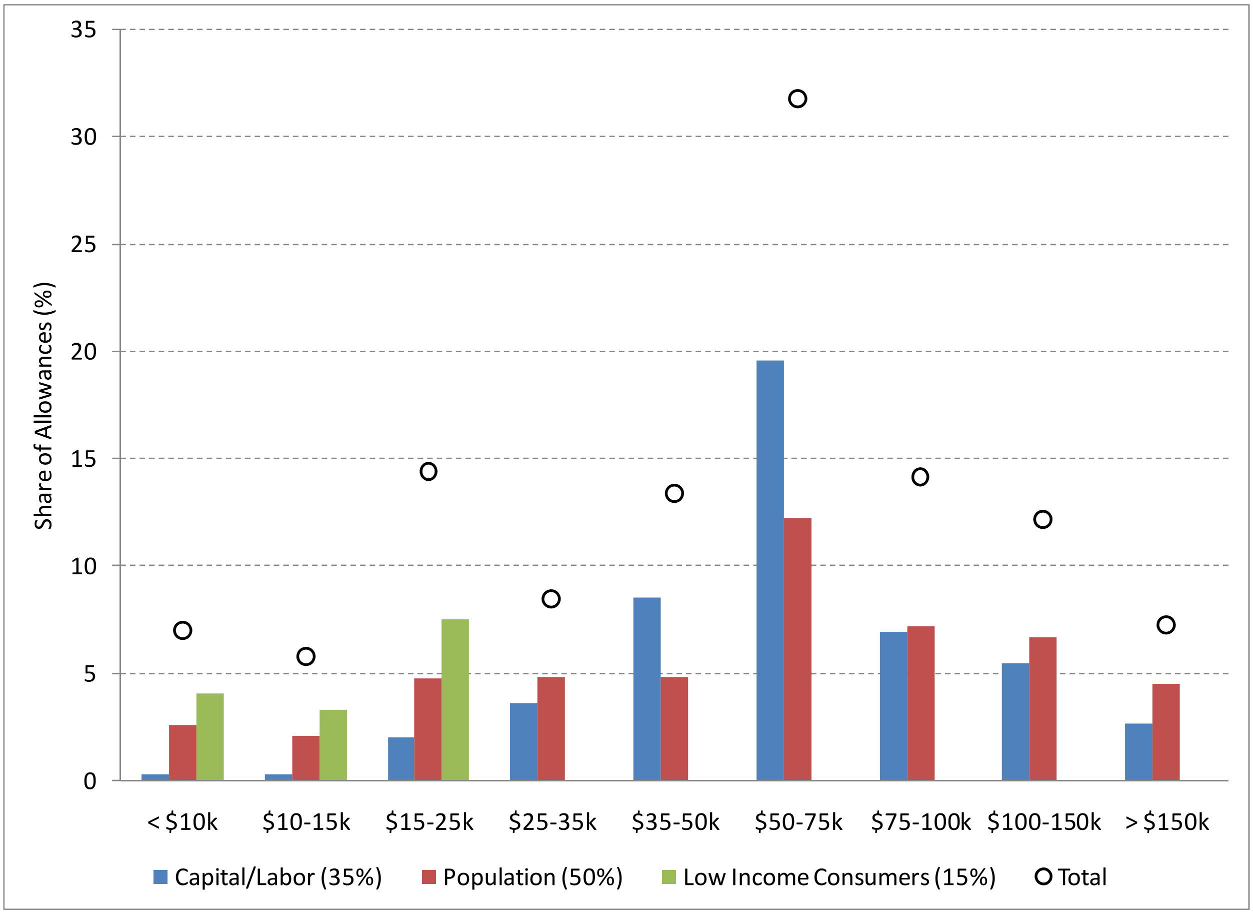
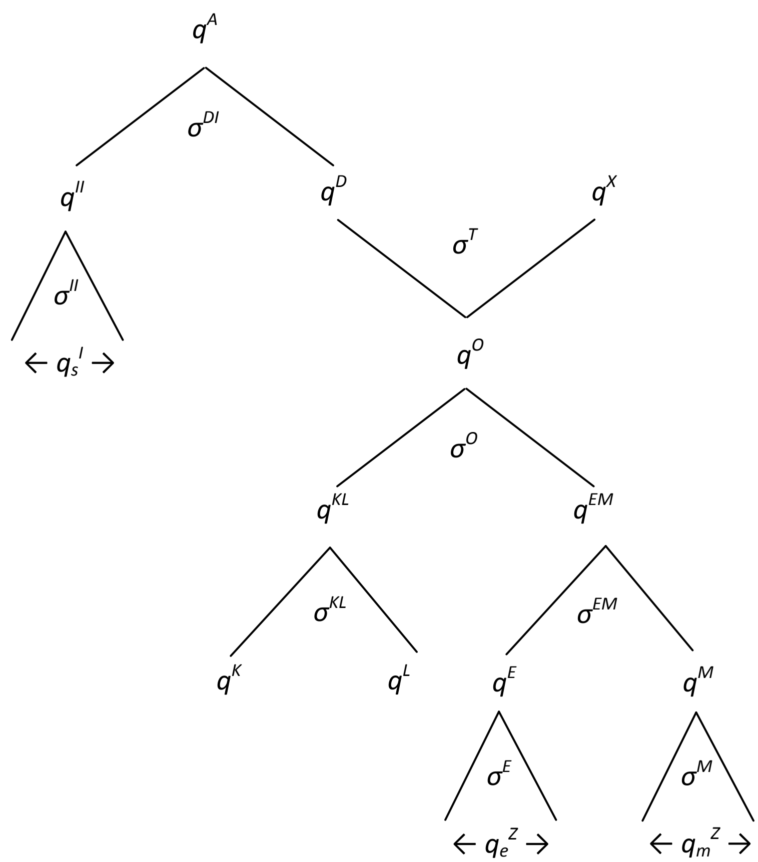


Figure 5. The Structure the CGE Model

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

A. Sectors and commodities



Key: q^O: sectoral output; q^{KL}: value added; q^{EM}: energy-materials composite; q^K: capital input; q^L: labor input; q^E: energy composite; q^M: materials composite; q_e^Z: *e* intermediate energy inputs; q_m^Z: *m* intermediate material inputs; q^D: output allocated to in-state demand; q^X: output allocated to satisfy import demands of other states and the rest of the world; q_s^I: demand for imports of output good from *s* states; q^{II}: import composite; q^A: Armington composite use of output good; σ^O = 0.6: elasticity of substitution between capital-labor and energy-material composites; σ^{KL} = 1: elasticity of substitution between capital and labor; σ^{EM} = 0.7: elasticity of substitution between energy and materials; σ^E = 0.8: elasticity of interfuel substitution; σ^M = 0.6: elasticity of substitution among intermediate material inputs; σ^T = 2: elasticity of transformation among domestic uses, and interstate and rest-of-world exports; σ^{II} = 8: elasticity of substitution among imports of output good from other states; σ^{DI} = 4: elasticity of substitution between domestic and imported varieties of output good.

B. Sectoral production structure

Figure 6. Baseline Emissions, Abatement and the Effects of Banking and Offset Provisions

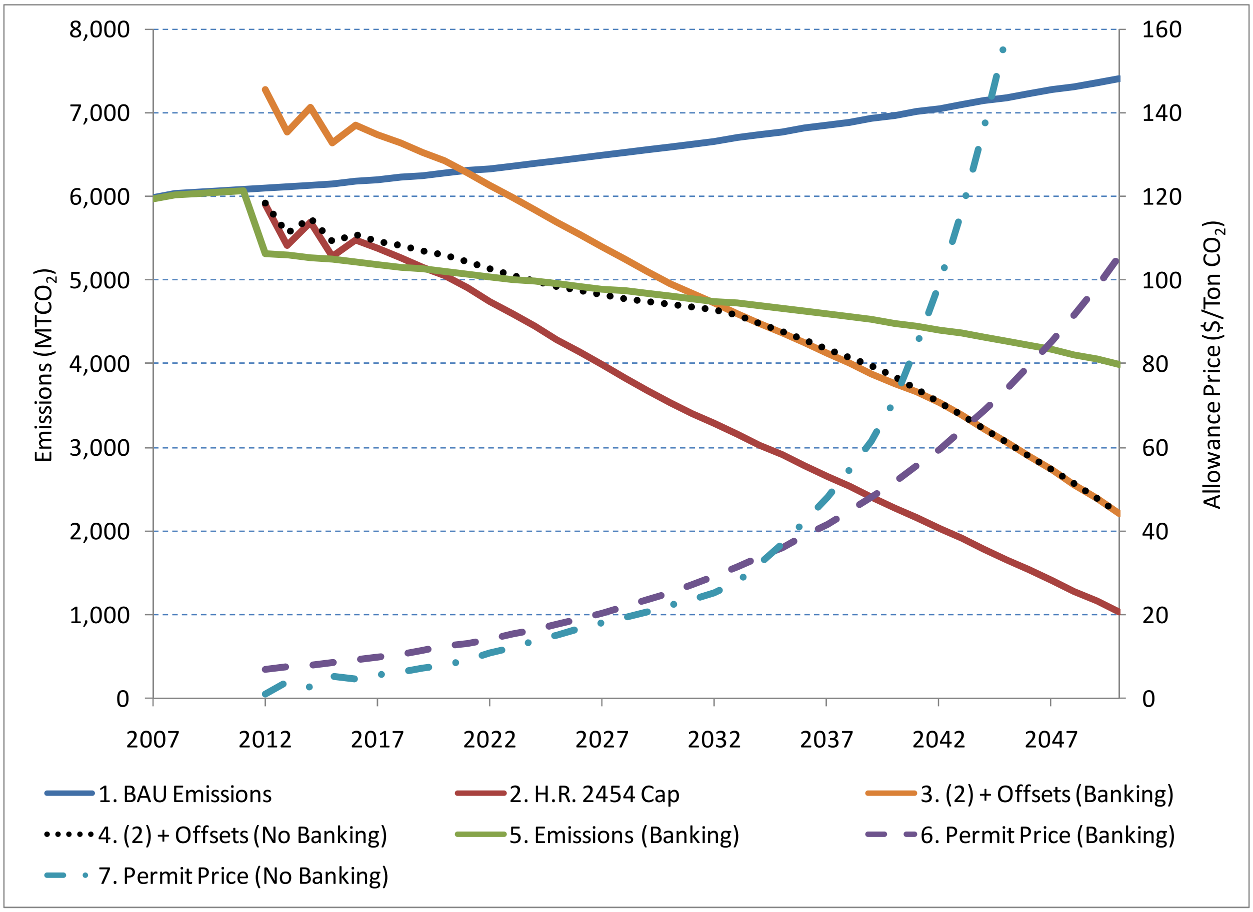
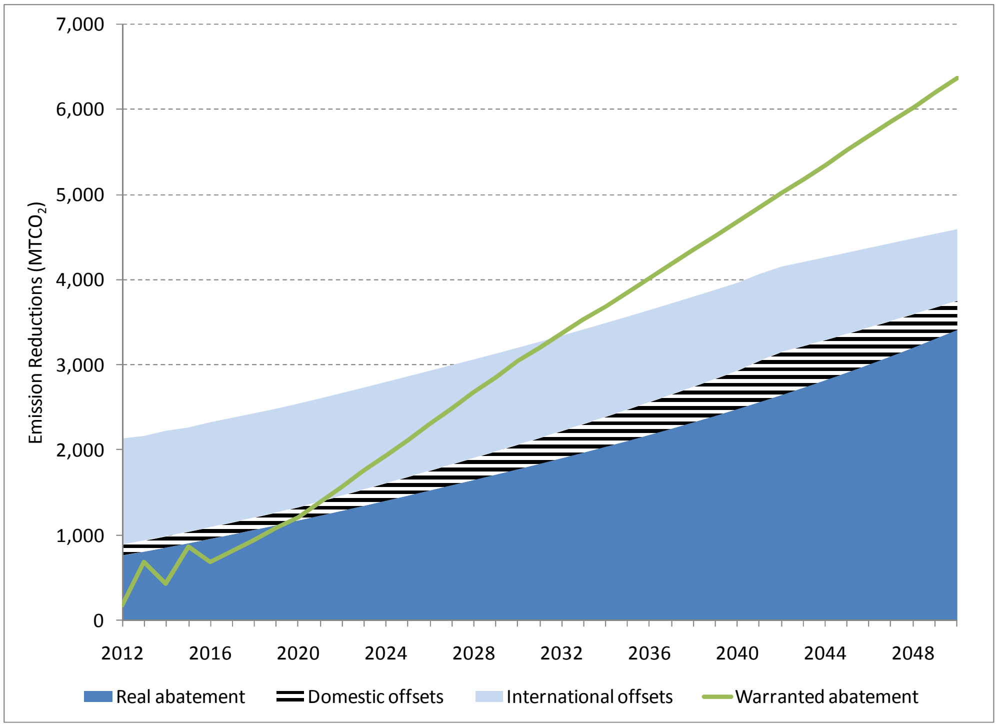
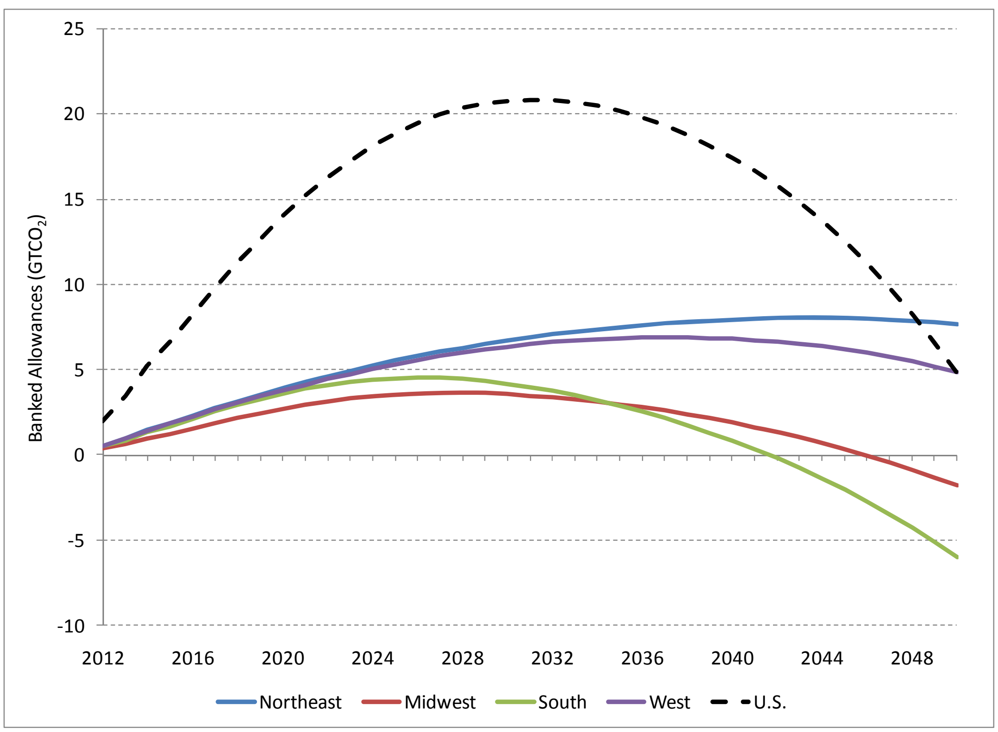


Figure 7. Emission Offsets and Banking

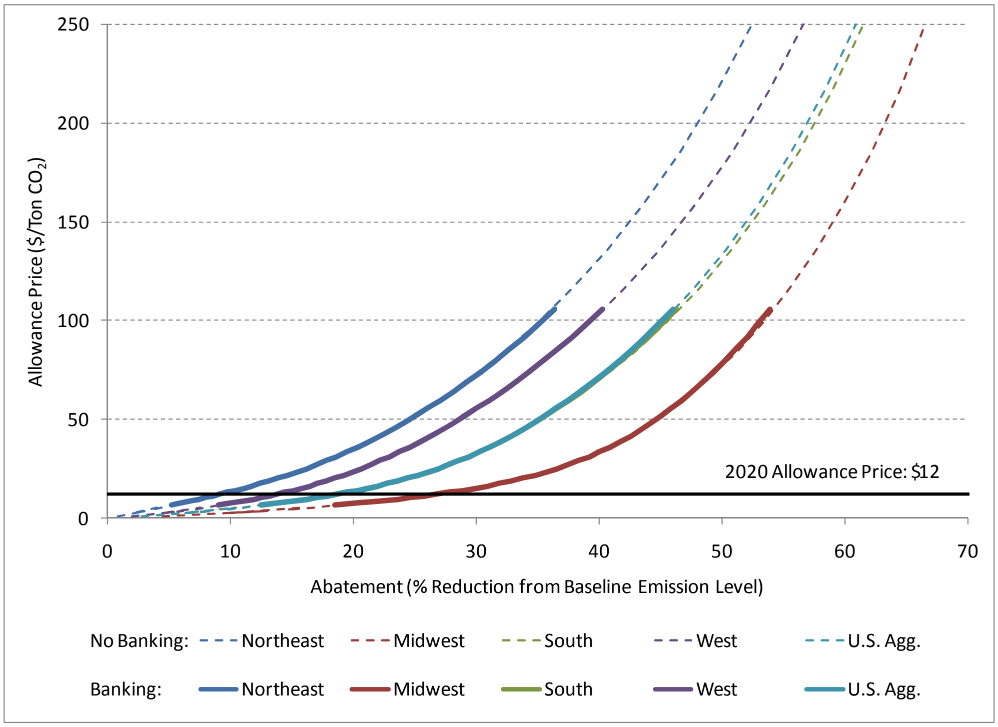


A. Contributions of offsets and abatement to compliance

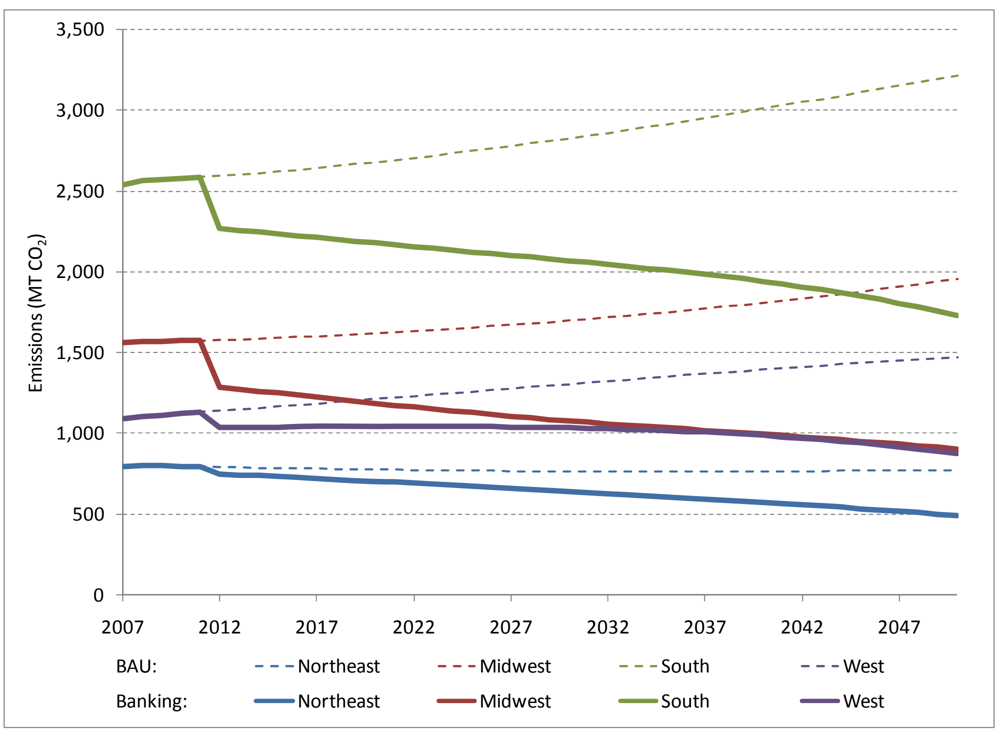


B. Banked allowances and offsets by region

Figure 8. Regional Emissions and Abatement

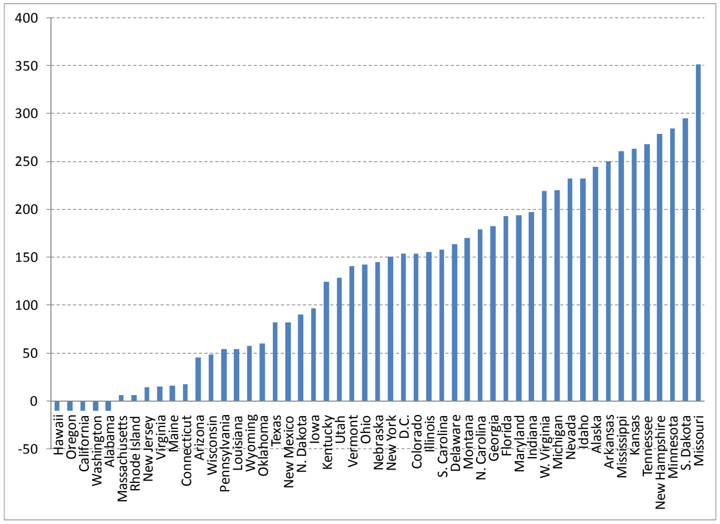


A. Long-run marginal abatement cost curves

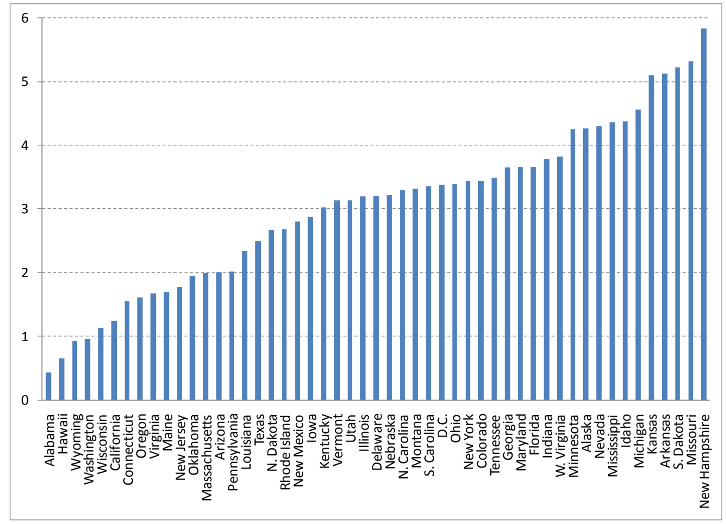


B. Baseline emissions and abatement

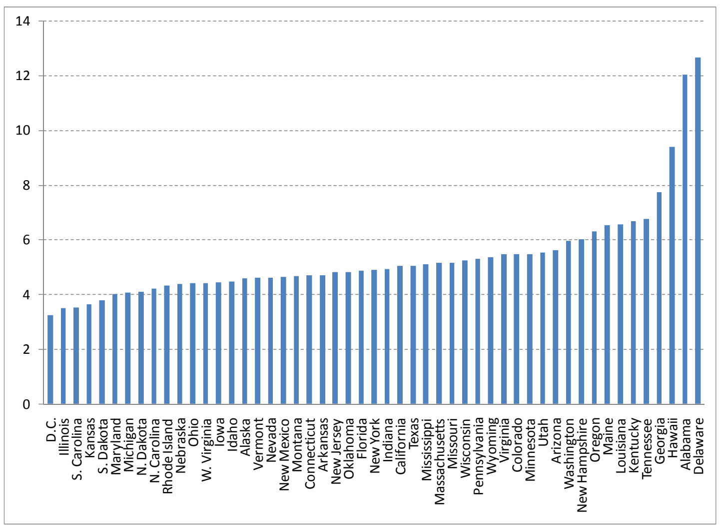
Figure 9. Interstate Energy Price Impacts, 2020 (% Change from BAU Price Level)



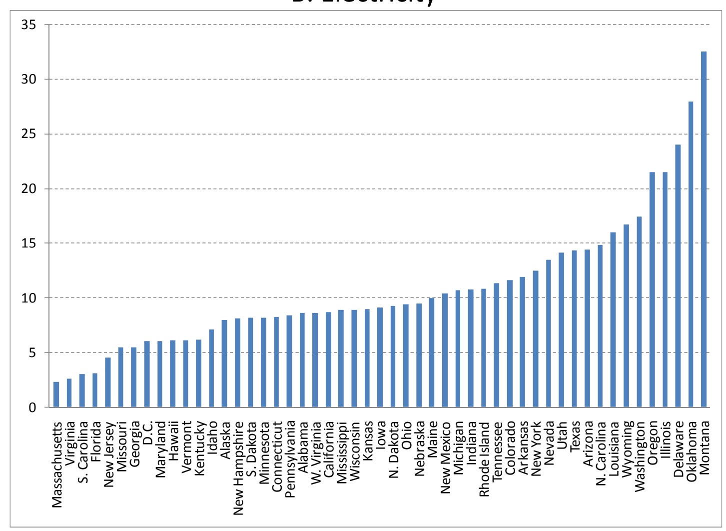
A. Coal



B. Electricity

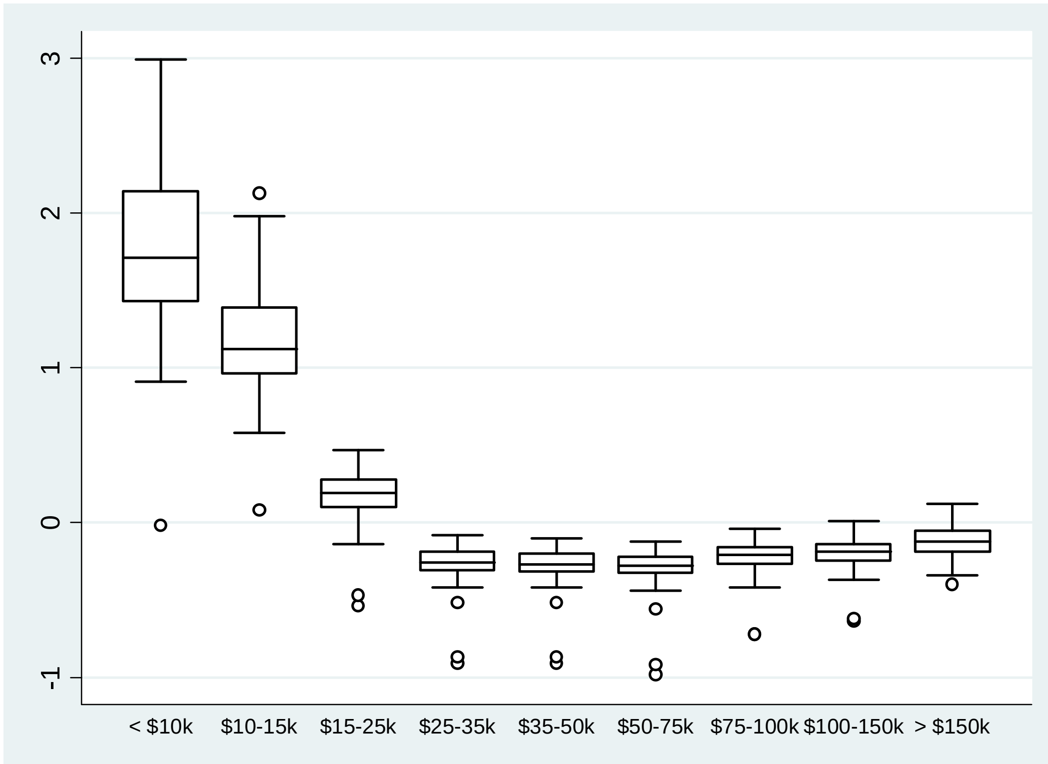


C. Petroleum

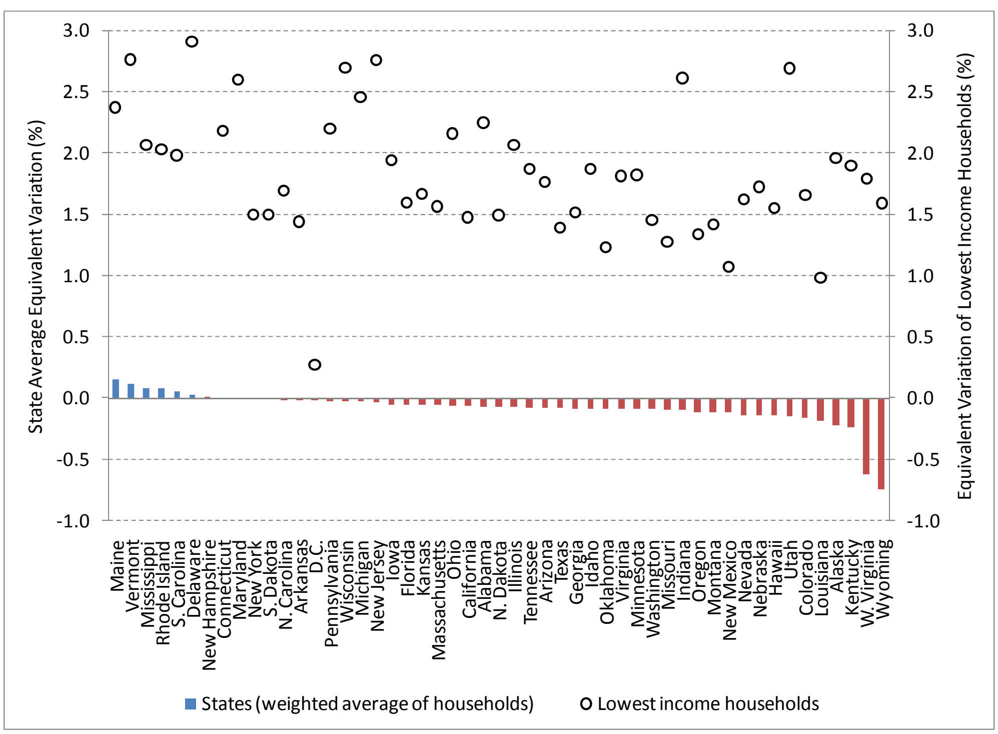


D. Natural gas

Figure 10. Summary of Welfare Impacts by Household Income and State, 2020 (% Equivalent Variation)

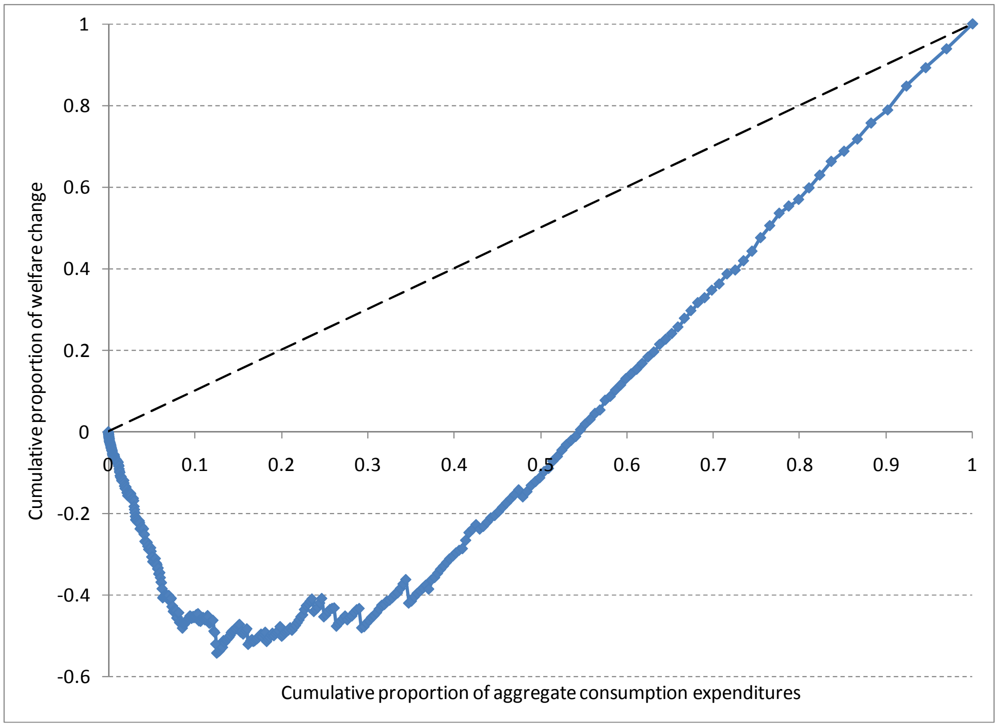


A. Distributions of welfare change (% equivalent variation) by household income

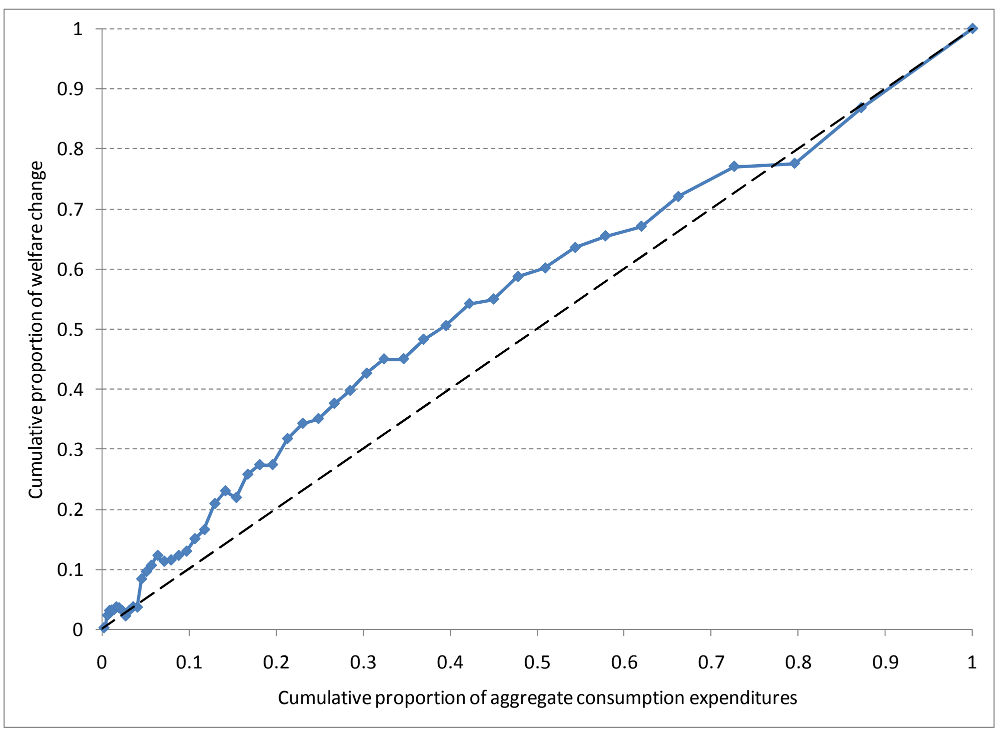


B. Interstate distributions of welfare change by household income

Figure 11. Lorenz Curves for the Consumption-Based Incidence of Title VII



A. Household income groups by state(n = 459)



B. States (n = 51)

Table 1. Allowance Allocation, 2012-2050

Category	2012	2016	2020	2030	2050	Nominal allocation rule
1. Electricity load distribution companies	39.38	31.50	31.50	-	-	(i) among LDCs based on electricity sales (1/2) and emissions (1/2); (ii) among ratepayers based on consumption shares
2. Small ELDC energy efficiency programs	0.50	0.50	0.50	-	-	Same as 1
3. Merchant coal electricity generators	4.38	3.50	3.50	-	-	Proportional to coal-fired generation
4. Long-term contract generators	1.88	1.51	1.51	-	-	Proportional to long-term contracts
5. Cogeneration at industrial parks	0.35	-	-	-	-	Negligible – omitted
6. Natural Gas load distribution companies	-	9.00	9.00	-	-	(i) among LDCs based on gas sales; (ii) among ratepayers according to consumption shares
7. Residential heating oil consumers	1.88	1.50	1.50	-	-	Proportional to heating oil consumption
8. Moderate/low-income consumers	15.00	15.00	15.00	15.00	15.00	Proportional to population in poorest quintile of households
9. Energy intensive industries	2.00	14.44	13.18	4.56	-	Proportional to manufacturing output x average emissions intensity, above 5% energy intensity by value, 15% gross trade exposure
10. Carbon capture and sequestration	-	1.75	5.00	5.00	5.00	Proportional to coal-fired generation
11. State efficiency and renewable energy programs	9.50	6.50	5.50	4.50	4.50	(i) among states based on energy consumption (1/3) and population (1/3), and divided equally (1/3); (ii) among ratepayers according to consumption shares
12. Building codes support for states	0.50	0.50	0.50	0.50	0.50	Proportional to population
13. Building retrofit program	0.05	0.05	0.03	0.03	0.03	Same as 12
14. Energy innovation hubs	0.45	0.45	0.45	0.45	0.45	Same as 12
15. Clean energy innovation centers	1.05	1.05	1.05	1.05	1.05	Same as 12
16. Clean cars	3.00	3.00	1.00	-	-	Proportional to vehicle manufacturing output
17. Oil refineries	-	2.00	2.00	-	-	Proportional to refinery output
18. Small business refiners	-	0.25	0.25	-	-	Same as 17
19. Climate change worker adjustment assistance fund	0.50	0.50	0.50	1.00	1.00	Proportional to labor force
20. Energy efficiency and renewables worker training	0.75	-	-	-	-	Same as 19
21. Domestic adaptation	0.90	0.90	0.90	3.90	3.90	Same as 12
22. Health adaptation	0.10	0.10	0.10	0.10	0.10	Same as 12
23. Wildlife and natural resource adaptation (auction)	0.39	0.39	0.39	1.54	1.54	Same as 12
24. Wildlife and natural resource adaptation (to states)	0.62	0.62	0.62	2.46	2.46	Same as 12
25. International adaptation	1.00	1.00	1.00	4.00	4.00	Auctioned, revenue sent overseas
26. International clean technology transfer	1.00	1.00	1.00	4.00	4.00	Same as 25
27. Supplemental reductions	5.00	5.00	5.00	3.00	2.00	Same as 25
28. Compensation for early actors	1.00	-	-	-	-	Negligible – omitted
29. Supplemental agricultural incentives program	0.14	0.14	-	-	-	Proportional to farm output
30. Supplemental renewable energy	0.14	0.14	-	-	-	Same as 12
Total allocated	91.44	102.28	100.97	51.09	45.53	
Residual allowances	8.56	-2.28	-0.97	48.91	54.47	Same as 12

Table 2. Allowance Allocation in Model

Category	Among States	Among household income groups
1. Electricity load distribution companies	Shares of national electricity consumption (1/2) and emissions (1/2)	(a) State allocation split based on ratio of residential to industrial/commercial electricity sales (b) Residential portion: shares of state gas consumption (c) Nonresidential portion: based on shares of state consumption of goods produced by industrial/commercial sectors
2. Small ELDC energy efficiency programs	Same as 1	Same as 1
3. Merchant coal electricity generators	Household x state shares of national capital income	
4. Long-term contract generators	Same as 3	
5. Cogeneration at industrial parks	Negligible – omitted	
6. Natural Gas load distribution companies	Shares of national gas consumption	(a) State allocation split based on ratio of residential to industrial/commercial gas sales (b) Residential portion: shares of state gas consumption (c) Nonresidential portion: shares of state consumption of goods produced by industrial/commercial sectors
7. Residential heating oil consumers	Shares of national heating oil consumption	Shares of state petroleum consumption
8. Moderate/low-income consumers	Household x state shares of population in poorest three household income groups	
9. Energy intensive industries	Household x state shares of national final consumption of goods produced by energy intensive sectors	
10. Carbon capture and sequestration	Same as 3	
11. State efficiency and renewable energy programs	Shares of national energy consumption (1/3) and population (1/3), and divided equally (1/3)	Shares of state electricity and gas consumption
12. Building codes support for states	Household x state shares of national population	
13. Building retrofit program	Same as 12	
14. Energy innovation hubs	Same as 12	
15. Clean energy innovation centers	Same as 12	
16. Clean cars	Same as 3	
17. Oil refineries	Same as 3	
18. Small business refiners	Same as 17	
19. Climate change worker adjustment assistance fund	Household x state shares of national labor income	
20. Energy efficiency and renewables worker training	Same as 19	
21. Domestic adaptation	Same as 12	
22. Health adaptation	Same as 12	
23. Wildlife and natural resource adaptation (auction)	Same as 12	
24. Wildlife and natural resource adaptation (to states)	Same as 12	
25. International adaptation	Same as 12	
26. International clean technology transfer	Same as 25	
27. Supplemental reductions	Same as 25	
28. Compensation for early actors	Negligible – omitted	
29. Supplemental agricultural incentives program	Household x state shares of national final consumption of agricultural goods	
30. Supplemental renewable energy	Same as 12	
Residual allowances	Same as 12	

Table 3. Interstate Distribution of Emissions and Allowances, 2020

A. Business-as-usual emissions ($MTCO_2$)

Connecticut	39	Illinois	307	Delaware	14	Arizona	204
Maine	13	Indiana	159	D.C.	40	Colorado	124
Massachusetts	93	Michigan	231	Florida	270	Idaho	30
New Hampshire	13	Ohio	244	Georgia	242	Montana	34
Vermont	7	Wisconsin	119	Maryland	123	Nevada	54
Rhode Island	10	Iowa	86	N. Carolina	143	New Mexico	40
New Jersey	128	Kansas	76	S. Carolina	67	Utah	64
New York	258	Minnesota	150	Virginia	137	Wyoming	27
Pennsylvania	217	Missouri	135	W. Virginia	47	Alaska	26
		Nebraska	63	Alabama	174	California	415
		N. Dakota	24	Kentucky	120	Hawaii	26
		S. Dakota	20	Mississippi	80	Oregon	63
				Tennessee	170	Washington	101
				Arkansas	55		
				Louisiana	147		
				Oklahoma	94		
				Texas	748		
Northeast	777	Midwest	1614	South	2671	West	1207

B. Share of allowance allocation (%)

Connecticut	1.1	Illinois	4.0	Delaware	0.4	Arizona	1.9
Maine	0.4	Indiana	2.7	D.C.	0.3	Colorado	1.7
Massachusetts	1.9	Michigan	3.3	Florida	5.0	Idaho	0.5
New Hampshire	0.4	Ohio	3.9	Georgia	3.0	Montana	0.4
Vermont	0.2	Wisconsin	1.8	Maryland	1.7	Nevada	1.0
Rhode Island	0.3	Iowa	1.2	N. Carolina	2.9	New Mexico	0.6
New Jersey	2.5	Kansas	1.0	S. Carolina	1.5	Utah	0.9
New York	4.8	Minnesota	1.8	Virginia	2.5	Wyoming	0.4
Pennsylvania	4.1	Missouri	2.1	W. Virginia	0.8	Alaska	0.3
		Nebraska	0.7	Alabama	1.9	California	9.8
		N. Dakota	0.3	Kentucky	1.9	Hawaii	0.4
		S. Dakota	0.3	Mississippi	1.0	Oregon	1.2
				Tennessee	2.2	Washington	2.1
				Arkansas	1.0		
				Louisiana	2.3		
				Oklahoma	1.4		
				Texas	9.8		
Northeast	15.9	Midwest	23.2	South	39.8	West	21.1

C. % Difference b/w. allowance allocation and BAU emissions (- short/+ long)

Connecticut	43	Illinois	-35	Delaware	26	Arizona	-53
Maine	64	Indiana	-14	D.C.	-57	Colorado	-33
Massachusetts	5	Michigan	-27	Florida	-6	Idaho	-18
New Hampshire	78	Ohio	-18	Georgia	-37	Montana	-41
Vermont	54	Wisconsin	-22	Maryland	-28	Nevada	-9
Rhode Island	72	Iowa	-28	N. Carolina	1	New Mexico	-18
New Jersey	1	Kansas	-32	S. Carolina	16	Utah	-29
New York	-5	Minnesota	-39	Virginia	-6	Wyoming	-22
Pennsylvania	-6	Missouri	-21	W. Virginia	-17	Alaska	-37
		Nebraska	-48	Alabama	-45	California	20
		N. Dakota	-31	Kentucky	-19	Hawaii	-29
		S. Dakota	-24	Mississippi	-37	Oregon	-7
				Tennessee	-33	Washington	3
				Arkansas	-4		
				Louisiana	-20		
				Oklahoma	-24		
				Texas	-34		
Northeast	3	Midwest	-27	South	-25	West	-12

D. Difference b/w. allowance allocation and actual emissions (MT, - short/+ long)

Connecticut	30	Illinois	-1	Delaware	6	Arizona	-25
Maine	10	Indiana	-12	D.C.	-16	Colorado	-27
Massachusetts	21	Michigan	25	Florida	29	Idaho	-2
New Hampshire	8	Ohio	4	Georgia	-42	Montana	-6
Vermont	4	Wisconsin	7	Maryland	24	Nevada	-6
Rhode Island	9	Iowa	-4	N. Carolina	25	New Mexico	-5
New Jersey	33	Kansas	-2	S. Carolina	20	Utah	-15
New York	108	Minnesota	-8	Virginia	19	Wyoming	-9
Pennsylvania	18	Missouri	1	W. Virginia	-8	Alaska	-13
		Nebraska	-10	Alabama	-6	California	126
		N. Dakota	-2	Kentucky	-21	Hawaii	-7
		S. Dakota	1	Mississippi	4	Oregon	-7
				Tennessee	-18	Washington	-6
				Arkansas	-8		
				Louisiana	-60		
				Oklahoma	-19		
				Texas	-212		
Northeast	242	Midwest	0	South	-283	West	-2

Table 4. Interstate Distribution of Economic Impacts, 2020

Northeast		Midwest		South		West	
A. % Change in real GDP							
Connecticut	-0.28	Illinois	-0.43	Delaware	-0.35	Arizona	-0.44
Maine	-0.30	Indiana	-0.53	D.C.	-0.37	Colorado	-0.43
Massachusetts	-0.32	Michigan	-0.41	Florida	-0.33	Idaho	-0.45
New Hampshire	-0.27	Ohio	-0.46	Georgia	-0.41	Montana	-0.65
Vermont	-0.27	Wisconsin	-0.39	Maryland	-0.33	Nevada	-0.39
Rhode Island	-0.31	Iowa	-0.45	N. Carolina	-0.36	New Mexico	-0.49
New Jersey	-0.33	Kansas	-0.44	S. Carolina	-0.36	Utah	-0.50
New York	-0.30	Minnesota	-0.41	Virginia	-0.38	Wyoming	-1.51
Pennsylvania	-0.41	Missouri	-0.45	W. Virginia	-1.65	Alaska	-0.50
		Nebraska	-0.58	Alabama	-0.72	California	-0.31
		N. Dakota	-0.65	Kentucky	-0.86	Hawaii	-0.39
		S. Dakota	-0.43	Mississippi	-0.52	Oregon	-0.38
				Tennessee	-0.50	Washington	-0.32
				Arkansas	-0.43		
				Louisiana	-0.60		
				Oklahoma	-0.51		
				Texas	-0.42		
B. % Change in real income							
Connecticut	-0.24	Illinois	-0.36	Delaware	-0.26	Arizona	-0.36
Maine	-0.16	Indiana	-0.41	D.C.	-0.42	Colorado	-0.39
Massachusetts	-0.28	Michigan	-0.33	Florida	-0.26	Idaho	-0.36
New Hampshire	-0.22	Ohio	-0.36	Georgia	-0.37	Montana	-0.48
Vermont	-0.18	Wisconsin	-0.31	Maryland	-0.26	Nevada	-0.35
Rhode Island	-0.20	Iowa	-0.37	N. Carolina	-0.29	New Mexico	-0.37
New Jersey	-0.27	Kansas	-0.36	S. Carolina	-0.24	Utah	-0.42
New York	-0.26	Minnesota	-0.37	Virginia	-0.34	Wyoming	-1.03
Pennsylvania	-0.30	Missouri	-0.39	W. Virginia	-0.98	Alaska	-0.48
		Nebraska	-0.47	Alabama	-0.47	California	-0.27
		N. Dakota	-0.47	Kentucky	-0.57	Hawaii	-0.36
		S. Dakota	-0.32	Mississippi	-0.31	Oregon	-0.34
				Tennessee	-0.41	Washington	-0.29
				Arkansas	-0.31		
				Louisiana	-0.48		
				Oklahoma	-0.40		
				Texas	-0.38		
C. % Change in real consumption							
Connecticut	0.09	Illinois	0.01	Delaware	0.12	Arizona	0.01
Maine	0.24	Indiana	-0.01	D.C.	0.07	Colorado	-0.08
Massachusetts	0.03	Michigan	0.06	Florida	0.04	Idaho	0.00
New Hampshire	0.10	Ohio	0.02	Georgia	0.00	Montana	-0.03
Vermont	0.21	Wisconsin	0.06	Maryland	0.09	Nevada	-0.05
Rhode Island	0.17	Iowa	0.04	N. Carolina	0.07	New Mexico	-0.03
New Jersey	0.05	Kansas	0.03	S. Carolina	0.15	Utah	-0.06
New York	0.08	Minnesota	0.00	Virginia	0.00	Wyoming	-0.66
Pennsylvania	0.06	Missouri	-0.01	W. Virginia	-0.54	Alaska	-0.14
		Nebraska	-0.06	Alabama	0.01	California	0.02
		N. Dakota	0.01	Kentucky	-0.15	Hawaii	-0.06
		S. Dakota	0.08	Mississippi	0.17	Oregon	-0.02
				Tennessee	0.01	Washington	0.00
				Arkansas	0.07		
				Louisiana	-0.10		
				Oklahoma	0.00		
				Texas	0.01		

Table 5. General Equilibrium Burdens by Household Income Group and Region, 2020

Household income in 2007	I < $10k	II $10k -$15k	III $15k -$25k	IV $25k -$35k	V $35k -$50k	VI $50k -$75k	VII $75k -$100k	VII $100k -$150k	IX > $150k
	A. Number of households ('000)								
2007 [a]	8,456	7,051	13,525	12,528	11,540	26,253	13,845	14,214	9,372
2020 [b]	9,419	7,884	15,115	14,037	12,937	29,428	15,536	15,986	10,640
	B. Baseline mean household income ('000 2007 $)								
2007 [a]	5.2	12.4	19.7	29.5	39.5	58.4	86.1	119.5	239.8
2020 [b]	8.0	17.3	24.8	36.7	49.3	72.3	109.0	152.2	311.6
	C. Direct burden (% Change in consumer spending due to energy prices)								
New England	0.16	0.17	0.17	0.15	0.14	0.14	0.11	0.11	0.11
Mid Atlantic	0.15	0.16	0.16	0.14	0.13	0.13	0.10	0.10	0.10
E. N. Central	0.19	0.20	0.20	0.18	0.16	0.16	0.12	0.12	0.13
W. N. Central	0.22	0.23	0.23	0.20	0.18	0.18	0.14	0.14	0.14
S. Atlantic	0.16	0.17	0.17	0.15	0.14	0.14	0.11	0.11	0.11
E. S. Central	0.23	0.24	0.25	0.22	0.20	0.20	0.15	0.15	0.16
W. S. Central	0.19	0.20	0.20	0.17	0.16	0.16	0.12	0.12	0.12
Mountain	0.20	0.21	0.21	0.19	0.17	0.17	0.13	0.13	0.13
Pacific	0.15	0.16	0.16	0.15	0.14	0.13	0.11	0.10	0.10
U.S.	0.18	0.19	0.19	0.17	0.15	0.15	0.12	0.11	0.11
	D. Indirect burden (% Change in consumer spending due to non-energy prices)								
New England	-0.09	-0.09	-0.09	-0.09	-0.10	-0.10	-0.10	-0.10	-0.10
Mid Atlantic	-0.10	-0.10	-0.10	-0.10	-0.11	-0.11	-0.11	-0.11	-0.11
E. N. Central	-0.13	-0.12	-0.12	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13
W. N. Central	-0.12	-0.12	-0.12	-0.12	-0.13	-0.13	-0.13	-0.13	-0.13
S. Atlantic	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
E. S. Central	-0.16	-0.16	-0.16	-0.16	-0.16	-0.17	-0.17	-0.17	-0.17
W. S. Central	-0.10	-0.10	-0.10	-0.10	-0.11	-0.11	-0.11	-0.11	-0.11
Mountain	-0.12	-0.12	-0.12	-0.12	-0.13	-0.13	-0.13	-0.13	-0.13
Pacific	-0.10	-0.10	-0.10	-0.10	-0.10	-0.11	-0.11	-0.11	-0.11
U.S.	-0.11	-0.11	-0.11	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
	E. Total burden (% Change in consumer spending due to prices only)								
New England	0.07	0.08	0.07	0.06	0.04	0.04	0.01	0.01	0.01
Mid Atlantic	0.05	0.06	0.06	0.04	0.02	0.02	-0.01	-0.01	-0.01
E. N. Central	0.07	0.08	0.08	0.05	0.03	0.03	-0.01	-0.01	-0.01
W. N. Central	0.10	0.11	0.11	0.08	0.05	0.05	0.01	0.01	0.01
S. Atlantic	0.04	0.05	0.05	0.03	0.02	0.01	-0.02	-0.01	-0.01
E. S. Central	0.07	0.09	0.09	0.06	0.04	0.03	-0.02	-0.02	-0.02
W. S. Central	0.08	0.10	0.10	0.07	0.05	0.05	0.01	0.01	0.01
Mountain	0.08	0.09	0.09	0.06	0.04	0.04	0.00	0.00	0.00
Pacific	0.05	0.06	0.06	0.04	0.03	0.03	0.00	0.00	0.00
U.S.	0.06	0.07	0.07	0.05	0.03	0.03	0.00	0.00	0.00
	F. % Change in real consumer spending								
New England	2.07	1.46	0.46	0.00	-0.03	-0.05	-0.04	-0.03	0.01
Mid Atlantic	1.99	1.36	0.40	-0.04	-0.07	-0.09	-0.07	-0.05	-0.01
E. N. Central	2.40	1.60	0.43	-0.11	-0.14	-0.17	-0.11	-0.09	0.00
W. N. Central	1.68	1.25	0.36	-0.10	-0.14	-0.16	-0.12	-0.09	-0.02
S. Atlantic	1.82	1.42	0.34	-0.11	-0.13	-0.14	-0.11	-0.08	-0.03
E. S. Central	2.11	1.35	0.31	-0.24	-0.27	-0.31	-0.23	-0.19	-0.07
W. S. Central	1.39	1.09	0.29	-0.13	-0.15	-0.17	-0.14	-0.12	-0.07
Mountain	1.76	1.09	0.25	-0.16	-0.19	-0.21	-0.18	-0.15	-0.10
Pacific	1.56	1.23	0.38	-0.06	-0.09	-0.09	-0.09	-0.08	-0.06
U.S.	1.84	1.33	0.36	-0.10	-0.13	-0.14	-0.11	-0.09	-0.04

[a] Computed using 2007 Current Population Survey and Consumer Expenditure Survey data. [b] Computed by scaling 2007 CPS data using the simulated baseline growth of income groups' total expenditures in each state and regression-based imputations of the numbers of households as a function of projected income and Census population forecasts.

Table 6. Welfare Impacts by Income Category and State, 2020 (% Equivalent Variation)

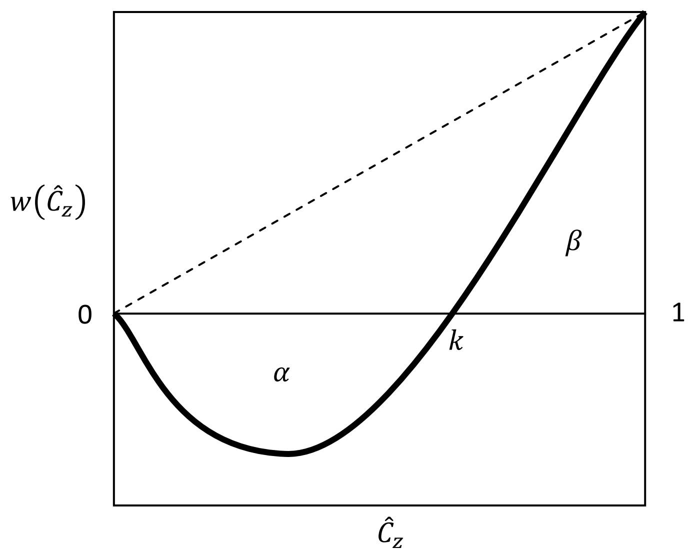
	I	II	III	IV	V	VI	VII	VII	IX	Avg.	Wtd. Avg.
						A. Northeast					
Connecticut	2.10	1.38	0.35	-0.08	-0.10	-0.11	-0.07	-0.05	-0.01	0.38	0.02
Maine	2.30	1.48	0.37	-0.05	-0.07	-0.09	-0.01	0.04	0.15	0.46	0.16
Massachusetts	1.48	1.06	0.25	-0.16	-0.18	-0.18	-0.16	-0.15	-0.13	0.20	-0.07
New Hampshire	2.98	1.79	0.41	-0.09	-0.10	-0.11	-0.07	-0.05	0.00	0.53	0.04
Vermont	2.71	1.67	0.39	-0.04	-0.05	-0.08	0.00	0.04	0.14	0.53	0.15
Rhode Island	1.94	1.38	0.38	-0.09	-0.11	-0.13	-0.07	-0.05	0.02	0.36	0.07
New Jersey	2.58	1.60	0.38	-0.16	-0.17	-0.18	-0.15	-0.14	-0.11	0.41	-0.04
New York	1.38	1.01	0.24	-0.13	-0.14	-0.15	-0.11	-0.10	-0.07	0.22	-0.01
Pennsylvania	2.08	1.18	0.19	-0.21	-0.22	-0.24	-0.17	-0.15	-0.07	0.26	-0.03
Connecticut	2.10	1.38	0.35	-0.08	-0.10	-0.11	-0.07	-0.05	-0.01	0.38	0.02
Maine	2.30	1.48	0.37	-0.05	-0.07	-0.09	-0.01	0.04	0.15	0.46	0.16
						B. Midwest					
Illinois	1.93	1.33	0.26	-0.25	-0.26	-0.28	-0.21	-0.19	-0.13	0.24	-0.11
Indiana	2.56	1.47	0.20	-0.30	-0.31	-0.34	-0.22	-0.18	-0.04	0.32	-0.09
Michigan	2.38	1.57	0.32	-0.22	-0.23	-0.25	-0.16	-0.14	-0.04	0.36	-0.04
Ohio	2.09	1.34	0.23	-0.26	-0.27	-0.29	-0.19	-0.16	-0.05	0.27	-0.07
Wisconsin	2.61	1.49	0.31	-0.22	-0.22	-0.24	-0.16	-0.13	-0.05	0.38	-0.04
Iowa	1.86	1.19	0.20	-0.25	-0.26	-0.29	-0.18	-0.14	-0.03	0.23	-0.08
Kansas	1.55	1.10	0.17	-0.27	-0.27	-0.29	-0.21	-0.18	-0.09	0.17	-0.11
Minnesota	1.68	1.14	0.23	-0.26	-0.27	-0.28	-0.22	-0.20	-0.15	0.19	-0.14
Missouri	1.17	0.88	0.12	-0.28	-0.28	-0.30	-0.22	-0.20	-0.13	0.09	-0.13
Nebraska	1.57	0.98	0.02	-0.40	-0.41	-0.43	-0.33	-0.29	-0.19	0.06	-0.23
N. Dakota	1.36	0.89	-0.01	-0.38	-0.39	-0.43	-0.30	-0.26	-0.12	0.04	-0.19
S. Dakota	1.39	1.00	0.16	-0.23	-0.24	-0.26	-0.17	-0.13	-0.03	0.17	-0.05
						C. South					
Delaware	2.80	1.92	0.40	-0.12	-0.13	-0.17	-0.07	-0.03	0.08	0.52	0.05
D.C.	-0.05	0.04	-0.16	-0.27	-0.27	-0.27	-0.27	-0.27	-0.27	-0.20	-0.25
Florida	1.49	1.07	0.19	-0.19	-0.20	-0.20	-0.17	-0.15	-0.13	0.19	-0.05
Georgia	1.37	1.18	0.16	-0.26	-0.27	-0.28	-0.23	-0.21	-0.16	0.14	-0.12
Maryland	2.47	2.06	0.46	-0.13	-0.15	-0.17	-0.11	-0.09	-0.03	0.48	0.00
N. Carolina	1.59	1.27	0.22	-0.18	-0.19	-0.20	-0.14	-0.12	-0.05	0.25	-0.02
S. Carolina	1.93	1.56	0.32	-0.14	-0.15	-0.17	-0.07	-0.04	0.08	0.37	0.09
Virginia	1.70	1.26	0.20	-0.20	-0.21	-0.22	-0.17	-0.16	-0.11	0.23	-0.08
W. Virginia	1.74	0.76	-0.69	-1.13	-1.12	-1.19	-0.93	-0.82	-0.51	-0.43	-0.67
Alabama	2.18	1.32	0.10	-0.45	-0.46	-0.50	-0.32	-0.26	-0.07	0.17	-0.11
Kentucky	1.83	0.98	-0.06	-0.58	-0.59	-0.63	-0.48	-0.43	-0.30	-0.03	-0.29
Mississippi	1.95	1.32	0.26	-0.32	-0.34	-0.36	-0.24	-0.20	-0.08	0.22	0.00
Tennessee	1.71	1.02	0.12	-0.35	-0.35	-0.36	-0.29	-0.26	-0.19	0.12	-0.14
Arkansas	1.33	0.98	0.15	-0.27	-0.28	-0.29	-0.22	-0.19	-0.13	0.12	-0.06
Louisiana	0.88	0.71	-0.05	-0.48	-0.48	-0.50	-0.41	-0.38	-0.29	-0.11	-0.27
Oklahoma	1.09	0.70	-0.01	-0.37	-0.37	-0.38	-0.31	-0.29	-0.22	-0.02	-0.19
Texas	1.23	0.89	0.09	-0.28	-0.28	-0.30	-0.25	-0.23	-0.18	0.08	-0.14
						D. West					
Arizona	1.55	0.90	0.08	-0.29	-0.29	-0.30	-0.24	-0.22	-0.15	0.12	-0.14
Colorado	1.48	0.87	0.08	-0.29	-0.31	-0.31	-0.28	-0.27	-0.25	0.08	-0.21
Idaho	1.73	0.90	0.08	-0.28	-0.29	-0.30	-0.22	-0.18	-0.09	0.15	-0.11
Montana	1.20	0.56	-0.14	-0.44	-0.45	-0.47	-0.35	-0.30	-0.17	-0.06	-0.24
Nevada	1.46	0.88	0.09	-0.26	-0.27	-0.27	-0.23	-0.22	-0.18	0.11	-0.15
New Mexico	0.96	0.61	0.02	-0.33	-0.34	-0.34	-0.29	-0.27	-0.22	-0.02	-0.17
Utah	2.48	1.32	0.13	-0.33	-0.34	-0.36	-0.30	-0.28	-0.22	0.23	-0.20
Wyoming	1.51	0.39	-0.76	-1.08	-1.08	-1.14	-0.93	-0.85	-0.60	-0.51	-0.83
Alaska	1.80	0.97	0.07	-0.38	-0.39	-0.40	-0.37	-0.37	-0.34	0.07	-0.29
California	1.40	1.09	0.25	-0.15	-0.16	-0.17	-0.14	-0.13	-0.11	0.21	-0.06
Hawaii	1.43	1.34	0.23	-0.26	-0.28	-0.28	-0.25	-0.25	-0.23	0.16	-0.17

Appendix: A Modified Suits Index of the Welfare Impacts of Cap and Trade

The ICGE model simulations generate grouped data on $z = 1, \ldots, n$ state × household income classes, each of whom consumes C_z in the no-policy scenario and experiences a welfare loss, W_z, defined as the reduction in real consumption expenditure, as a result of the emission limit. The most widely used measure of the progressivity of burden of the policy is the Suits Index, which on a consumption basis has the discrete approximation:

$$S \approx 1 - \sum_{z=0}^{n} \left(w(\hat{C}_z) + w(\hat{C}_{z-1}) \right) (\hat{C}_z - \hat{C}_{z-1})$$

where $\hat{C}_z$ is the cumulative proportion of consumption and $w(\hat{C}_z)$ is the corresponding cumulative proportion of welfare losses. The formula for the Suits Index is the same that for the Gini coefficient for income distribution, except that the latter sums the cumulative proportion of income corresponding to the cumulative proportion of population.



The formula above is appropriate if $w(\hat{C}_z) \geq 0 \; \forall z$, but must be modified in the case where $w(\hat{C}_z) < 0$ for some z, which is precisely the situation which arises in the paper. Figure 11.A demonstrates that poor households experience a welfare gain (negative welfare loss), which results in the Lorenz curve for welfare losses dipping below the horizontal axis for almost half its domain, similar to the stylized figure above. To obtain a summary measure of the progressivity of Title VII it is necessary to construct a Suits Index with negative tax liabilities, which is the analogue of computing a Gini coefficient with negative income, a procedure for which was devised by Chen et al. (1982) and Berrebi and Silber (1985). With reference to the figure above, these authors demonstrate that the Gini coefficient—or the Suits Index—can be calculated from the areas α and β defined by the crossing point, k, as

$$S^* \approx \frac{1 + 2(\alpha - \beta)}{1 + 2\alpha}$$

where α and β can be found by applying the trapezoid approximation to the model's results:

$$\alpha = -\frac{1}{2}\sum_{\mathrm{z}=0}^{\mathrm{k}} \left(\mathrm{w}(\hat{C}_{\mathrm{z}}) + \mathrm{w}(\hat{C}_{\mathrm{z}-1})\right)(\hat{C}_{\mathrm{z}} - \hat{C}_{\mathrm{z}-1})$$

$$\beta = \frac{1}{2}\sum_{z=k+1}^{n} \left(\mathrm{w}(\hat{C}_{\mathrm{z}}) + \mathrm{w}(\hat{C}_{\mathrm{z}-1})\right)(\hat{C}_{\mathrm{z}} - \hat{C}_{\mathrm{z}-1})$$

West and Williams (2004) develop a somewhat different modification for situations in which one tax is raised and another is lowered. Their procedure is employed by Burtraw et al. (2008).