MIT Joint Program on the Science and Policy of Global Change

Distributional Impacts of a U.S. Greenhouse Gas Policy: A General Equilibrium Analysis of Carbon Pricing

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Report No. 182
November 2009

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Distributional Impacts of a U.S. Greenhouse Gas Policy: A General Equilibrium Analysis of Carbon Pricing[†]

Sebastian Rausch[*], Gilbert E. Metcalf[‡§], John M. Reilly[*], and Sergey Paltsev[*]

Abstract

We develop a new model of the U.S., the U.S. Regional Energy Policy (USREP) model that is resolved for large states and regions of the U.S. and by income class and apply the model to investigate a $15 per ton CO_2 equivalent price on greenhouse gas emissions. Previous estimates of distributional impacts of carbon pricing have been done outside of the model simulation and have been based on energy expenditure patterns of households in different regions and of different income levels. By estimating distributional effects within the economic model, we include the effects of changes in capital returns and wages on distribution and find that the effects are significant and work against the expenditure effects. We find the following:

First, while results based only on energy expenditure have shown carbon pricing to be regressive we find the full distributional effect to be neutral or slightly progressive. This demonstrates the importance of tracing through all economic impacts and not just focusing on spending side impacts.

Second, the ultimate impact of such a policy on households depends on how allowances, or the revenue raised from auctioning them, is used. Free distribution to firms would be highly regressive, benefiting higher income households and forcing lower income households to bear the full cost of the policy and what amounts to a transfer of wealth to higher income households. Lump sum distribution through equal-sized household rebates would make lower income households absolutely better off while shifting the costs to higher income households. Schemes that would cut taxes are generally slightly regressive but improve somewhat the overall efficiency of the program.

Third, proposed legislation would distribute allowances to local distribution companies (electricity and natural gas distributors) and public utility commissions would then determine how the value of those allowances was used. A significant risk in such a plan is that distribution to households might be perceived as lowering utility rates That reduced the efficiency of the policy we examined by 40 percent.

Finally, the states on the coasts bear little cost or can benefit because of the distribution of allowance revenue while mid-America and southern states bear the highest costs. This regional pattern reflects energy consumption and energy production difference among states. Use of allowance revenue to cut taxes generally exacerbates these regional differences because coastal states are also generally higher income states, and those with higher incomes benefit more from tax cuts.

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[†] This paper was written for the American Tax Policy Institute Conference on Energy Taxation held in Washington, D.C., on Oct. 15 -16, 2009

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1. INTRODUCTION

The United States is moving closer to enacting comprehensive climate change policy. President Obama campaigned in 2008 in part on a platform of re-engaging in the international negotiations on climate policy and supported a U.S. cap and trade policy with 100 percent auctioning of permits. Congress has moved rapidly in 2009 with the House of Representatives voting favorably on the American Clean Energy and Security Act of 2009 (H.R. 2454) in late June of that year. What will happen in the Senate is still unresolved as this is written.

H.R. 2454 establishes a cap and trade system to reduce greenhouse gas emissions 17 percent below 2005 levels by 2020 and 83 percent by 2050. In addition it contains, among other provisions, new energy efficiency standards for various appliances and a renewable electricity standard requiring retail suppliers to meet 20 percent of their electricity demand through renewable sources and energy efficiency by 2020 (see Holt and Whitney (2009) for a detailed description of the bill).

Cap and trade legislation acts like a tax in raising the price of carbon based fuels and other covered inputs that release greenhouse gases. The monies involved in a cap and trade program are significant. The Congressional Budget Office estimated last June that H.R. 2454 would increase federal revenues by nearly $850 billion between 2010 and 2019. Since the bulk of permits are freely allocated in early years of the program spending would also increase over that period by roughly $820 billion.[1]

This paper uses a new computable general equilibrium model of the U.S. economy, the MIT U.S. Regional Energy Policy (USREP) model, to assess the distributional impacts of carbon pricing whether in the form of a cap-and-trade system or a carbon tax. Sectoral detail, the production structure, and parameters of the USREP model are similar to those of the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005a). While EPPA is a global model, with the U.S. one of its regions, USREP explicitly models only the U.S. This sacrifice of global coverage, allows explicit modeling of regions and states within the U.S., and multiple household income classes in each region. As with the EPPA model, the USREP model has rich detail on energy production and consumption making it particularly suitable for analyzing energy and climate change legislation.

With multiple regions and incomes classes the USREP model is especially useful for evaluating the distributional effects of policy. Many of the provisions of H.R. 2454 are designed to blunt the impact of the legislation on lower and middle income households, and to balance regional effects. Given the potential for strong distributional effects of climate policy, whether something close to H.R. 2454 passes or not, attending to distributional impacts is likely to be an important feature of any eventual policy.[2] To date, much of the distributional analysis has been done as a side calculation based on the energy and CO_2 prices, simulated in models like EPPA,

[1] See Congressional Budget Office (2009b). The CBO treats freely allocated permits as both revenue and spending. Ignoring impacts on other tax revenues the free allocation of $100 of permits would be scored as $100 of revenue and $100 of spending. CBO's scoring approach is described in Congressional Budget Office (2009a).

[2] See, for example, the testimony of Burtraw (2009) before the Senate Committee on Finance.

and on energy expenditure shares in different regions and among households of different income classes. Such analyses fail to take into account the distribution implications of changes in wages and returns on capital, or how CO_2 pricing will translate into different energy price impacts in different regions. The design of USREP allows direct consideration of these issues, endogenously calculating effects on each household type. We consider a number of possible ways of using the revenue from carbon pricing to show how these strongly affect households at different income levels and in different regions.

The first focus of economists is often on the efficiency of policy and as diagramed in introductory economics texts these are "welfare triangles." Observers of the policy process in Washington often note that who gets what and who pays is a far more important consideration in pushing policy forward or stopping it than efficiency considerations. Who gets what and who pays in the diagrams of economic texts are rectangles of which the triangles are only a small fraction. A Washington economic policy quip is that rectangles trump triangles every time, a warning that to be relevant to policy the distributional effects are key. Moreover, who ends up bearing costs in a market system is also not automatically intuitive. Who writes the check for the tax bill has little to do with who actually bears the cost. Economists refer to this as the incidence of a tax, and it can be passed forward to consumers, backward to asset owners, and can affect labor and capital returns. USREP offers the ability to examine such distributional effects.

2. BACKGROUND

Carbon pricing has very similar impacts to broad based energy taxes – not surprising since over eighty percent of greenhouse gas emissions are associated with the combustion of fossil fuels (U.S. Environmental Protection Agency (2009)). The literature on distributional implications across income groups of energy taxes is a long and extensive one and some general conclusions have been reached that help inform the distributional analysis of carbon pricing. First, analyses that rank households by their annual income find that excise taxes in general tend to be regressive (e.g. Pechman (1985) looking at excise taxes in general and Metcalf (1999) looking specifically at a cluster of environmental taxes). The difficulty with this ranking procedure is that many households in the lowest income groups are not poor in any traditional sense that should raise welfare concerns. This group includes households that are facing transitory negative income shocks or who are making human capital investments that will lead to higher incomes later in life (e.g. graduate students). It also includes many retired households which may have little current income but are able to draw on extensive savings.

That current income may not be a good measure of household well being has long been known and has led to a number of efforts to measure lifetime income. This leads to the second major finding in the literature. Consumption taxes – including taxes on energy – look considerably less regressive when lifetime income measures are used than when annual income measures are used. Studies include Davies *et al.* (1984), Poterba (1989, 1991), Bull *et al.* (1994), Lyon and Schwab (1995) and many others.[3]

The lifetime income approach is an important caveat to distributional findings from annual incidence analyses but it relies on strong assumptions about household consumption decisions. In particular it assumes that households base current consumption decisions knowing their full stream of earnings over their lifetime. While it is reasonable to assume that households have some sense of future income, it may be implausible to assume they have complete knowledge or that they necessarily base spending decisions on income that may be received far in the future.[4] It may be that the truth lies somewhere between annual and lifetime income analyses. This paper takes a current income approach to sorting households.

Turning to climate policy in particular a number of papers have attempted to measure the distributional impacts of carbon pricing across household income groups. Dinan and Rogers (2002) build on Metcalf (1999) to consider how the distribution of allowances from a cap and trade program affects the distributional outcome. Both these papers emphasize that focusing on the revenue from carbon pricing (either a tax or auctioned permits) provides an incomplete distributional analysis. How the proceeds from carbon pricing are distributed have important impacts on the ultimate distributional outcome.

The point that use of carbon revenues matters for distribution is the basis for the distributional and revenue neutral proposal in Metcalf (2007) for a carbon tax swap. It is also the focus of the analysis in Burtraw *et al.* (2009). This latter paper considers five different uses of revenue from a cap and trade auction focusing on income distribution as well as regional distribution. A similar focus on income and regional distribution is done by Hassett *et al.* (2009). This last paper does not consider the use of revenue but does compare both annual and lifetime income measures as well as a regional analysis using annual income. Grainger and Kolstad (2009) do a similar analysis as that of Hassett *et al.* (2009) and note that the use of household equivalence scales can exacerbate the regressivity of carbon pricing. Finally Burtraw *et al.* (2009) consider the distributional impacts in an expenditure side analysis where they focus on the allocation of permits to local distribution companies (LDCs), an issue to which we turn below.

All of the papers above assume that the burden of carbon pricing is shifted forward to consumers in the form of higher energy prices (and higher prices of energy-intensive consumption goods and services). That carbon pricing is passed forward to consumers follows from the analysis of a number of computable general equilibrium models. Bovenberg and Goulder (2001), for example, find that coal prices rise by over 90 percent of a $25 per ton carbon tax in the short and long run (Table 2.4).[5] This incidence result underlies their finding that only a

[3] Most of these studies look at a snapshot of taxes in one year relative to some proxy for lifetime income – often current consumption based on the permanent income hypothesis of Friedman (1957). An exception is Fullerton and Rogers (1993) who model the lifetime pattern of tax payments as well as income.

[4] On the other hand casual observation of graduate students in professional schools (business, law, medicine) make clear that many households are taking future income into account in their current consumption decisions.

[5] They assume world pricing for oil and natural gas so that the gross of tax prices for these two fossil fuels rise by the full amount of the tax.

small percentage of permits need be freely allocated to energy intensive industries to compensate shareholders for any windfall losses from a cap and trade program. See also Bovenberg *et al.* (2005) for more on this issue.

Metcalf *et al.* (2008) consider the degree of forward shifting (higher consumer prices) and backward shifting (lower factor returns) over different time periods for a carbon tax policy begun in 2012 and slowly ramped up through 2050. The tax on carbon emissions from coal are largely passed forward to consumers in all years of the policy in roughly the same magnitude found by Bovenberg and Goulder (2001). Roughly ten percent of the burden of carbon pricing on crude oil is shifted back to oil producers initially with the share rising to roughly one-fourth by 2050 as consumers are able to find substitutes for oil in the longer run. Interestingly the consumer burden of the carbon tax on natural gas exceeds the tax. This reflects the sharp rise in demand for natural gas as an initial response to carbon pricing is to substitute gas for coal in electricity generation. By 2050 the producer price is falling for reasonably stringent carbon policies.[6]

Fullerton and Heutel (2007) construct an analytic general equilibrium model to identify the various key parameters and relationships that determine the ultimate burden of a tax on a pollutant.[7] While the model is not sufficiently detailed to provide a realistic assessment of climate change impacts on the U.S. economy it illustrates critical parameters and relationships that drive burden results.

The general equilibrium models discussed above all assume a representative agent in the U.S. thereby limiting their usefulness to considering distributional questions. Metcalf *et al.* (2008) apply results from a representative agent model to data on U.S. households that allows them to draw conclusions about distributional impacts of policies but the household heterogeneity is not built into the model.[8]

Several computable general equilibrium (CGE) models have been constructed to investigate regional implications of climate and energy in the U.S. For example, the ADAGE model, documented in Ross (2008), has a U.S. regional module which is usually aggregated to five or six regions. The MRN-NEEM model described in Tuladhar *et al.* (2009) has nine U.S. regions. Both these models use a single representative household in each region.

The USREP model described in the next section marks an advance in the literature and climate change policy modeling by allowing for heterogeneity across income groups and regions in the U.S. Among other things the model allows us to test the reasonableness of previous model assumptions about complete forward shifting of carbon pricing to consumers. We turn to that model now.

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[6] Distributional results depend importantly on the stringency of policy. How stringent the policy is affects whether carbon free technologies are adopted in the EPPA model and therefore what the relative demand for fossil fuels is. In the text above we are reporting carbon tax results for a policy that limits emissions to 287 billion metric tons over the control period.

[7] The paper also provides a thorough summary of the literature on the incidence impacts of environmental taxes.

[8] A recent paper by Bento *et al.* (2009) marks an advance in the literature by allowing for household heterogeneity over income and location. That paper considers the impact of increased U.S. gasoline taxes taking into account new and used car purchases along with scrappage and changes in driving behavior.

3. THE USREP MODEL

The USREP model merges together economic data from IMPLAN (Minnesota IMPLAN Group, 2008) with physical energy data from Energy Information Administration's State Energy Data System (SEDS). Most of the basic data are at the state level and so there is flexibility in the regional structure. We aggregate from the state level to regions, with the regional aggregations determined to capture difference in electricity costs and to help focus on how regions and states differ. A detailed technical description of the model and issues involved in merging these two data sets together into a consistent economic data base are described in an Appendix to the paper. Here we briefly describe the key components of the model.

3.1 Households

The USREP model is a multi-region, multi-sector, multi-household CGE model of the U.S. economy for analyzing U.S. energy and greenhouse gas policies with a capability to assess impacts on regions, sectors and industries, and different household income classes. As in any classical Arrow-Debreu general equilibrium model, our framework combines behavioral assumptions on rational economic agents with the analysis of equilibrium conditions, and represents price-dependent market interactions as well as the origination and spending of income for various economic agents based on microeconomic theory. Profit-maximizing firms produce goods and services using intermediate inputs from other sectors and primary factors of production from households. Utility-maximizing households receive income from government transfers and from supplying factors of production to firms which they spend on buying goods and services. The government collects tax revenue which is spent on consumption and household transfers. The USREP model implemented here is a static model calibrated to 2006 data. It distinguishes 12 regions which are aggregations of U.S. states as defined in **Table 1** and visualized in **Figure 1**.[9] Consistent with the assumption of perfect competition on product and factor markets, production processes exhibit constant-returns-to-scale and are modeled by nested constant-elasticity-of-substitution (CES) functions. A schematic overview of the nesting structure for each production sector is provided in the Appendix. Non-energy activities are aggregated into five sectors, as shown in the table. [10] The energy sector, which emits several of the non-CO_2 gases as well as CO_2, is modeled in more detail. The static USREP model is a first development phase toward a dynamic model similar to EPPA. In this analysis we apply a relatively low CO_2 price, $15 per ton CO_2-equivalent with the intent of showing results relevant to the first few years of a climate policy. The static version of the model incorporates electricity

[9] Alaska is a region in the model, and we simulate policy in it but we do not report results because we do not have the same degree of confidence in results for this region as we do for other regions. Alaska results are highly sensitive to minor changes in modeling scenarios because of the small population in the state. Merging Alaska with other regions, on the other hand, is problematic given the unique energy characteristics of the state.

[10] A detailed discussion of the adopted nesting structure and its empirical relevance to reflect substitution possibilities among various inputs, in particular with regard to fuels and electricity, can be found in Paltsev *et al*, (2005).

Table 1. USREP Model Details.

Region [a]	**Sectors**	**Factors**
Alaska (AK)	**Non-Energy**	Capital
California (CA)	Agriculture (AGRIC)	Labor
Florida (FL)	Services (SERV)	Crude Oil Resources
New York (NY)	Energy-Intensive (EINT)	Natural Gas Resources
New England (NENGL)	Other Industries (OTHR)	Coal Resources
South East (SEAST)	Transportation (TRAN)	Nuclear Resources
North East (NEAST)	**Energy**	Hydro Resources
South Central (SCENT)	Coal (COAL)	
North Central (NCENT)	Crude Oil (OIL)	
Mountain (MOUNT)	Refined Oil (ROIL)	
Pacific (PACIF)	Natural Gas (GAS)	
	Electric: Fossil (ELEC)	
	Electric: Nuclear (NUC)	
	Electric: Hydro (HYD)	

[a]*Model regions are aggregations of the following U.S. states: NENGL = Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island; SEAST = Virginia, Kentucky, North Carolina, Tennessee, South Carolina, Georgia, Alabama, Mississippi; NEAST = West Virginia, Delaware, Maryland, Wisconsin, Illinois, Michigan, Indiana, Ohio, Pennsylvania, New Jersey, District of Columbia; SCENT = Oklahoma, Arkansas, Louisiana; NCENT = Missouri, North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa; MOUNT = Montana, Idaho, Wyoming, Nevada, Utah, Colorado, Arizona, New Mexico; PACIF = Oregon, Washington, Hawaii.*

generation from fossil fuel, nuclear and hydro power and existing fuels, but not the array of advanced technologies in EPPA. Electricity outputs generated from different technologies are assumed to be perfect substitutes. We constrain the expansion of nuclear and hydro power to no more than a 20 percent relative to the benchmark level, or given this structure, production from these sources can expand without bound. Other advanced technologies would only be relevant at higher CO_2 prices and further into the future, and so we believe the static model, as formulated, is appropriate to study the effects of a relatively modest GHG pricing policy implemented in the near term.

Economic modeling often distinguishes between short- and long-run effects. In the short-run agents have a limited ability to adjust to changed prices while in the long-run they adjust completely within the constraints of available technology. Because capital is fully mobile in the static USREP model, the analysis conducted here is closest to a long-run result. While potential backstop technologies are not specified, they are unlikely to be relevant at at CO_2 price of \$15. Hence, results of the USREP show the impact we would expect of implementing a CO_2 price of \$15 (and maintaining it) allowing 20 or 30 years for the economy to adjust to this level.[11]

We assume labor is fully mobile across industries in a given region but is immobile across U.S. regions. Labor supply is determined by the household choice between leisure and labor (e.g., Babiker *et al.* (2003)). Capital is mobile across regions and industries. We assume an integrated U.S. market for fossil fuel resources and assume for the core model that the regional

[11] Immobility of labor among regions is consistent with an intermediate run. Note also that a comparative statics analysis can be set to capture long run effects its does not capture growth effects which are important in tax recycling cases we investigate.

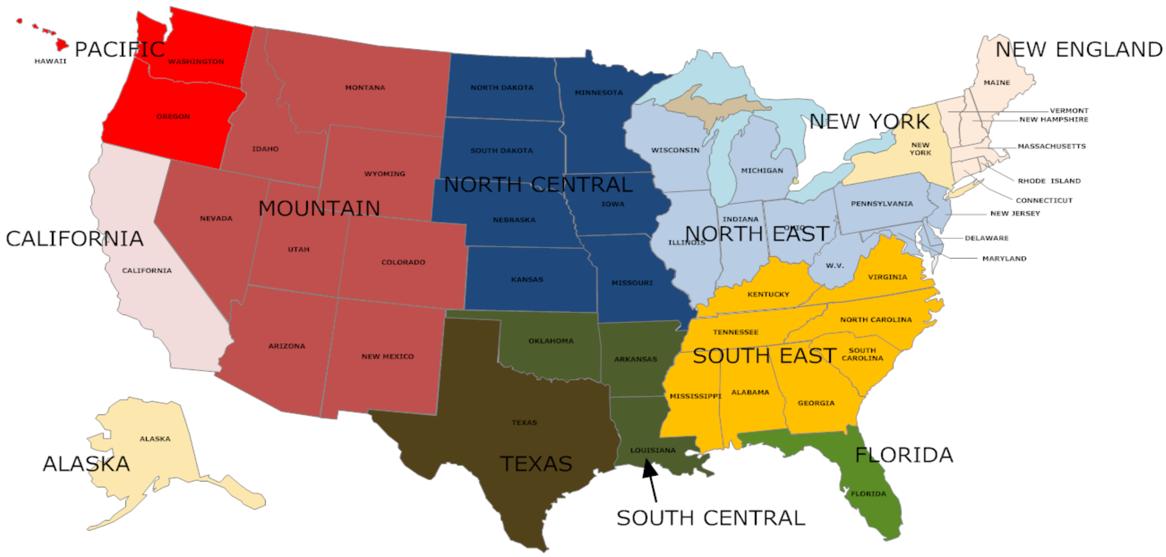

Figure 1. Regional Aggregation in the USREP Model.

ownership of resources is distributed in proportion to capital income.[12] Savings enters directly into the utility function which generates the demand for savings and makes the consumption-investment decision endogenous. We follow an approach by Bovenberg *et al.* (2005) distinguishing between capital that is used in production of market goods and services and capital used in households (e.g. the housing stock). We assume income from the former is subject to taxation while the imputed income from housing capital is not. A more detailed discussion of the nesting structure of total consumption can be found in Paltsev *et al.* (2005a).

We distinguish nine representative household types for each region based on different income classes as defined in **Table 2**. We use a linearly homogeneous CES structure to describe preferences of households implying that the income elasticity is unity and does not vary with income.[13] Household heterogeneity refers both to a different structure in terms of income sources as well as expenditures. The nesting structure is illustrated in Appendix A.

3.2 Government

Conventional tax rates are differentiated by region and sector and include both federal and state taxes. Revenue from these taxes is assumed to be spent in each region, proportional to its current levels. This takes account of varying state tax levels, and the current distribution of the spending of Federal tax revenue among the states. Different assumptions are possible but the intent here to keep a focus on the implications of CO_2 pricing and revenue distribution, and not

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[12] Given the lack of data describing the regional ownership of fossil fuel resources in the U.S., we use capital income as a proxy.

[13] We have experimented with a linear expenditure demand system where consumption is measured relative to subsistence levels, and calibrated preferences to empirically plausible values for income elasticities ranging from 0 to 1. We found that this very slightly increases welfare costs for low income classes. Overall quantitative effects for the type of policy analyses that we consider here are negligible.

Table 2. Income Classes Used in the USREP Model and Cumulative Population.

Income class	Description	Cumulative Population for whole U.S. (in %)[a]
hhl	Less than $10,000	7.3
hh10	$10,000 to $15,000	11.7
hh15	$15,000 to $25,000	21.2
hh25	$25,000 to $ $30,000	31.0
hh30	$30,000 to $50,000	45.3
hh50	$50,000 to $75,000	65.2
hh75	$75,000 to $100,000	78.7
hh100	$100,000 to $150,000	91.5
hh150	$150,000 plus	100.0

[a]Based on Consumer Expenditure Survey Data for 2006.

muddy that by assuming changes in distribution of other Federal or State tax revenues. The USREP model includes ad-valorem output taxes, corporate capital income taxes, and payroll taxes (employers' and employees' contribution). These tax rates are calculated on the basis of IMPLAN data which provides data on inter-institutional tax payments. In the case of capital income taxes this allows us to calculate average tax rates only. We incorporate marginal personal income tax rates based on data from the NBER TAXSIM tax simulator. We use the NBER data together with IMPLAN data on total personal income tax payments to estimate slope coefficients of a linear income tax schedule for each income class and region capturing a non-linear income tax across the entire income range.

3.3. Trade

Sectoral output produced in each region is converted through a constant-elasticity-of-transformation function into goods destined for the regional, national, and international market. All goods are tradable. Depending on the type of commodity, we distinguish three different representations of intra-national regional trade. First, bilateral flows for all non-energy goods are represented as "Armington" goods (Armington (1969)), where like goods from other regions are imperfectly substitutable for domestically produced goods. Second, domestically traded energy goods, except for electricity, are assumed to be homogeneous products, i.e. there is a national pool that demands domestic exports and supplies domestic imports. This assumption reflects the high degree of integration of intra-U.S. markets for natural gas, crude and refined oil, and coal. Third, we differentiate six regional electricity pools that are designed to provide an approximation of the existing structure of independent system operators (ISO) and the three major NERC interconnections in the U.S. More specifically, we distinguish the Western, Texas ERCOT and the Eastern NERC interconnections and in addition identify AK, NENGL, and NY as separate regional pools.[14] [15] We assume that within each regional pool traded electricity is a homogenous good and that there is no electricity trade between regional pools.

Analogously to the export side, we adopt the Armington (1969) assumption of product heterogeneity for imports. A CES function characterizes the trade-off between imported (from national and international sources) and locally produced varieties of the same goods. Foreign closure of the model is determined through a national balance-of-payments (BOP) constraint. Hence, the total value of U.S. exports equals the total value of U.S. imports accounting for an initial BOP deficit given by the base year statistics. The BOP constraint thereby determines the real exchange rate which indicates the (endogenous) value of the domestic currency vis-à-vis the foreign currency.

The U.S. economy as a whole is modeled as a large open economy, by specifying elasticities for world export demand and world import supply functions. Thus, while we do not explicitly model other regions, the simulations include terms of trade and competitiveness effects of policies that approximate results we would get with a full global model.

4. SCENARIOS AND ANALYSIS

We model a greenhouse gas policy that establishes a price on all greenhouse gases of $15 per metric ton of carbon dioxide equivalents.[16] We describe the scenarios in terms of a cap and trade system but stress that the analysis applies equally to a carbon tax applied to the same base. A cap and trade system in which all permits are auctioned by the government is economically equivalent to a carbon tax. In both cases carbon pricing raises the price of fossil fuels and carbon intensive products while raising revenue for the federal government. A cap and trade system in which the permits are freely allocated according to some rule (or set of rules) can be decomposed into a two-part policy. In the first part permits are fully auctioned. In the second part the auction revenue is distributed in a manner that mirrors the free distribution of permits. For that reason we do not focus on whether permits are auctioned or not but rather focus in the different scenarios on how the revenue is returned to the economy.[17] That is, returning revenue to agents in the economy is equivalent, for modeling purposes, of distributing allowances to them which they would then sell and receive payment for equal to the CO_2 price.[18]

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[14] We identify NY and NENGL as separate pools since electricity flows with contiguous ISOs represent only a small fraction of total electricity generation in those regions. For example, based on own calculation from data provided by ISOs, net electricity trade between ISO New England and ISO New York account for less than 1% of total electricity produced in ISO New England. Interface flows between the New York and neighboring ISOs amount to about 6% of total electricity generation in ISO New York.

[15] The regional electricity pools are thus defined as follows: NENGL, NY, TX, AK each represent a separate pool. The Western NERC interconnection comprises CA, MOUNT, and PACIF. The Eastern NERC interconnection comprises NEAST, SEAST, and FL.

[16] The greenhouse gases are converted to carbon dioxide equivalents (CO_2e) using 100 year global warming potentials from the IPCC Second Assessment Report, those specified in most policy measures.

[17] Our two part decomposition suggests a broader point, emphasized by Weisbach (2009), that the differences between taxes and cap and trade systems are, on many dimensions, more apparent than real.

[18] There may be political economy considerations in whether the allowances are distributed or the allowances are auction and the revenue distributed, but those do not affect the model results.

Table 3. Overview of Scenarios.

Scenario	Description
LUMPSUM	Revenue is recycled through uniform lump-sum transfers per household.
PAYRTAX	Revenue is recycled through a uniform cut in payroll taxes.
MPITR	Revenue is recycled through a uniform cut in marginal personal income tax rates.
CAPTAX	Revenue is recycled through a uniform cut in average capital income tax.
CAPITAL	Revenue is allocated in proportion to capital income.
ELE_LS	Revenue is allocated in proportion to capital income except for revenue going to the electricity sector. Here revenue is allocated in proportion to electricity consumption.
ELE_SUB	Revenue is allocated in proportion to capital income except for allowances going to the electricity sector. Here revenue is assumed to subsidize the domestic consumer electricity price.

In order to facilitate comparisons across the various scenarios we fix government revenue relative to GDP at the same level as in the reference (no policy) scenario, which we define as revenue neutrality.[19] This means that not all carbon pricing revenue is available for recycling purposes as some is required to replace losses in other tax revenues as economic activity is affected by the policy. We impose this requirement as a constraint in the model to calculate endogenously in each simulation the amount needed to be held back, rather than assume a fixed percentage of revenue to cover losses in other tax revenues as is done by the Congressional Budget Office (viz. Congressional Budget Office (2009a)). We consider seven different scenarios that differ in terms of how the revenues are returned to households. In all cases policy effects are assessed with respect to a reference scenario where no policy changes apply.

Table 3 provides a full list of scenarios. In the *LUMPSUM* scenario the revenue from a carbon tax or cap and trade program is distributed by means of a uniform lump-sum transfer. Due to tax base erosion, and given the revenue-neutrality constraint, only some part of total allowance revenue can be recycled. We endogenously determine the level of lump-sum payment that satisfies revenue-neutrality and give all households an equal transfer amount.[20]

The next three scenarios recycle climate revenue by lowering existing taxes. The *PAYRTAX* scenario uniformly reduces the payroll tax rate across all workers. The *MPITR* scenario reduces marginal tax rates for the personal income tax by the same amount (in percentage point terms). Finally the *CAPTAX* scenario lowers capital income tax rates by the same amount (in percentage

[19] Some analysts define revenue neutrality as the absolute level of revenue, but we observe that over time tax revenue has remained at about the same share of GDP.

[20] The USREP model, as described, has a representative household for each income class in each region. To determine the distribution, we use data from the U.S. Census Bureau on the number of regional households in each income class, to weight the distribution to each income class by the actual number of households.

point terms). While these three scenarios are perhaps most easily thought of in terms of a green tax reform they are all possible with a cap and trade system with fully auctioned permits.

The final three scenarios return the revenue in ways intended to represent free allocation of allowances. The value of allowances allocated freely to industrial emitters or upstream producers of fossil fuels would generate a windfall gain for these firms, and those gains would accrue to equity owners of the firm. This would be equivalent to distributing the revenue from auctioned permits or taxes to the equity holders in these firms. The *CAPITAL* scenario assumes that the distribution of holdings is similar to the distribution of holdings of all capital income. We do not have data on how holdings of capital in carbon-intensive firms may differ among regions or income levels but this approach captures the fact that in general higher income households own more equity than low income households.

The American Clean Energy and Security Act of 2009 allocates a portion of permits to local gas and electricity distribution companies to be used to offset the higher costs of gas and electricity by retail customers. The legislation prohibits the use of the permit value for lowering gas or electricity rates, but leaves unclear how those funds will be distributed. It is also not clear how utilities subject to rate of return regulation will be treated in rate setting proceedings at the state level. We assume that regulated rate-of-return industries would not be allowed to retain the windfall gain associated with the value of allowances distributed to them, but that the gain would go to rate payers.

While the legislation attempts to preserve the efficiency of passing through higher prices to consumers, an important question is whether or not that will done in a way that consumers perceive as effectively lowering prices. If electricity bills include higher prices, and the funds are rebated separately (for example, at the end of the year) consumers may indeed perceive higher electricity prices in their monthly bills. This possibility is modeled by treating the distribution as lump-sum rebates based on electricity expenditure in the *ELE_LS* scenario. However, if utilities rebate allowance value back to consumers in their monthly bill, even if they separately detail the electricity costs at high prices and the rebate, consumers may just see the low final bill and assume that reflects lower electricity rates. In the *ELE_SUB* scenario we assume that the value of electricity sector allowances is passed on to consumers by subsidizing the domestic consumer price for electricity at an endogenously determined rate to capture this possible response. In both scenarios, we assume that all non-electricity allowances are distributed on the basis of capital income. The *ELE_SUB* scenario is an effort to capture a possible behavioral response by consumers in which they misperceive the true price of electricity, or that the intent of the legislation, to have rates reflect the full CO_2 costs, is somehow frustrated by PUC rate setting.[21]

[21] Burtraw *et al.* (2009) also consider different consumer responses to different LDC allocation schemes. Since they only focus on the electricity sector they cannot assess the overall efficiency consequences of different allocation schemes.

Table 4. Policy Impacts on Climate.

CO_2 Emissions	5,902.0
Non-CO_2 Emissions	1,055.7
Reduction in CO_2 Emissions From Reference Case	19.3%
Reduction in non-CO_2 Emissions From Reference Case	27.1%

Note: Emissions are reported for the Reference Case in million metric tons.

We begin by reporting results from the model for the U.S. as a single region where we focus on heterogeneity in income across households. We then consider regional variation and finally report results in which we allow for heterogeneity across households and regions. Before turning to those results, however, we report some summary impact measures for the climate policy analyses.

Table 4 reports greenhouse gas emissions in the reference (no policy) scenario as well as the reduction in emissions following the imposition of a $15 per metric ton carbon price. The bulk of the reduction in emissions comes from carbon dioxide though the percentage reduction in non-CO_2 emissions is higher. Aggregate emissions fall by 20.5 percent for the $15 carbon price.

An important driver of the final burden of climate policy is its impact on fossil fuel prices. **Table 5** reports prices for the various regions in our model as well as the carbon price as a percentage of that base price. Price data are taken from the Energy Information Administration database on state energy consumption and expenditures and include federal and state taxes on fuels. On average a $15 per ton carbon price would raise the price of coal by nearly three-quarters if the price is fully passed forward to consumers while the prices of natural gas and refined oil would increase by less than ten percent.

How much of the carbon price is passed forward to consumers in the form of higher prices for goods and services as opposed to being passed back to factors of production (capital, labor) as well as resource owners depends on a large number of economic parameters including various supply and demand elasticities. **Table 6** reports results from the USREP model on the extent of forward and backward shifting of carbon prices for a $15 per ton CO_2e charge.

For the U.S. as a whole the carbon price on coal is predominantly passed forward to purchasers of coal (primarily electric utilities). This reflects the low level of rents in coal reserves given coal's abundance. Carbon pricing on natural gas is also largely passed forward but to a somewhat lesser extent than for coal. While the consumer price for coal rises by over 90 percent of the carbon price, the consumer price for natural gas only rises by three-quarters. For this analysis, we assume that world oil prices are unaffected by U.S. carbon policy so the entire impact is borne by consumers of refined oil products.[22] To the extent that carbon pricing is passed back to factors of production and resource owners the burden of climate policy may differ

[22] U.S. oil consumption is sufficiently large that the assumption of zero impact is unrealistic. In other analyses where we have explicitly modeled world oil production and consumption, we find that approximately 80 percent of the tax is passed forward in the form of higher crude oil prices, but that analysis also included measures in other developed countries and so the impact of just U.S. policy on oil price would be less than that.

Table 5. Relationship between \$15 per ton CO_2-e Price and 2006 Average Fuel Prices.

	Coal		Natural Gas		Refined Oil	
	Base Price ($/short ton)	Added Cost (%)	Base Price ($/tcf)	Added Cost (%)	Base Price ($/gal)	Added Cost (%)
AK	43.42	66	4.77	17	2.10	6
CA	44.07	65	9.19	9	2.31	5
FL	52.81	54	9.43	9	2.08	6
MOUNT	28.70	100	9.54	9	2.36	5
NCENT	25.34	114	10.10	8	2.28	5
NEAST	36.00	80	12.20	7	2.33	5
NENGL	62.99	46	10.96	7	2.36	5
NY	50.14	57	11.54	7	2.19	6
PACIF	32.81	88	16.09	5	2.22	6
SCENT	29.97	96	8.46	10	2.19	6
SEAST	46.74	62	11.14	7	2.19	6
TX	30.73	94	7.21	11	2.04	6
US	40.31	71	10.05	8	2.22	6

Note: No adjustment for the effects of the policy on producer price. All prices are in 2006 dollars. Source: Fuel prices are based on DOE EIA price data and refer to average prices over all end-use categories and states in a given region.

significantly from the results of modeling in which carbon prices are fully passed forward. The USREP model allows us to disentangle both forward and backward shifting as well as which factors of production (labor or capital) and resource owners are disproportionately affected. In the model with regional disaggregation we can also account for differences in impacts given the differences (albeit minor) among regions in the degree of forward and backward shifting as shown in Table 6. In the model with an aggregate consumer and one region, we find that the wage falls by 0.6 percentage points and the rental rate to capital 0.8 percentage points. While these are relatively small percentage changes relative to the changes in energy prices, wage and capital income makes up virtually all of a households income, whereas changes in energy prices affect only a fraction of consumer expenditure. Hence the changes in wages and returns to capital can be as important as changes in energy prices in determining distributional effects. With regional heterogeneity we find that wage rates fall by different amounts as we discuss below. The last column of Table 6 shows how higher energy costs affect the price of electricity. Nationally electricity prices rise by nearly 13 percent. The price increase varies across regions – not surprising given the different mixes of fuel sources for electricity across regions as we discuss later.

The requirement that government spending as a share of GDP be unchanged means that not all of the revenue from carbon pricing can be recycled to households in the form of lower taxes or lump sum subsidies. At the national level a carbon price of \$15 per ton of CO_2e would raise

Table 6. Impacts on Fuel Prices Inclusive and Exclusive of GHG Charge (in %).

	Coal		**Natural Gas**		**Refined Oil**		**Electricity**
	inclusive	exclusive	inclusive	exclusive	inclusive	exclusive	inclusive
AK	50.6	-15.0	14.8	-4.6	3.0	-2.4	3.5
CA	71.8	-6.4	10.2	-3.1	4.7	-0.2	8.5
FL	72.8	-5.4	11.5	-3.1	5.1	0.0	9.9
MOUNT	89.5	-10.6	9.9	-2.3	4.8	-0.2	14.8
NCENT	76.2	-6.8	11.1	-1.7	5.3	0.2	19.8
NEAST	69.4	-7.9	9.5	-3.3	5.1	0.0	14.2
NENGL	73.8	-4.5	9.5	-1.4	4.9	0.0	12.0
NY	71.8	-6.4	10.6	-0.7	5.0	0.0	7.5
PACIF	33.1	-4.2	13.5	-1.1	4.9	0.4	1.7
SCENT	81.5	-6.6	8.2	-2.8	5.0	0.0	12.3
SEAST	68.8	-7.4	9.3	-2.8	5.2	0.1	15.2
TX	76.5	-7.2	8.6	-4.2	5.0	-0.3	8.2
US	72.9	-6.9	9.8	-2.9	5.1	0.0	12.8

$83 billion in 2006 dollars. However the change in economic activity due to the higher price of carbon intensive goods and services leads to a decline in non-greenhouse gas revenue of $42.1 billion relative to the reference scenario. In the final equilibrium just over half the revenue from carbon pricing is available for redistribution to households in some form or other.[23]

4.1 Decomposing General Equilibrium Effects of Carbon Pricing

It is a well-established fact that carbon pricing by itself is regressive if the analysis of the costs is based on income class-specific energy expenditure patterns (e.g., Metcalf (2007), Burtraw *et al.* (2009) and Hassett *et al.* (2009)). As already noted, we find that carbon pricing affects income through reduced factor prices for capital, labor and fossil fuel resources, and so as a result the relative sources of income of households at different level incomes will affect income distribution. At the lowest income levels a larger fraction of income is from government transfers and these transfers are not directly affected by carbon pricing. As discussed above the impact on capital returns is larger than the impact on wages, with higher income households deriving more of their income from capital returns. These basic facts mean that the income effect of carbon pricing is likely to be progressive, at least partly offsetting the regressive expenditure effect. The virtue of a general equilibrium framework is its ability to capture both expenditure and income effects in a comprehensive manner.

[23] This contrasts to CBO's assumption that 25 percent of the revenue from a cap and trade system or carbon tax would need to be set aside to offset declines in other tax collections. In simulations not reported here, we find the loss in tax revenue to be sensitive to the international trade closure assumptions—how much impact U.S. changes has on world prices. The larger the impact on world prices, the less the erosion of U.S. activity with less impact on tax revenue.

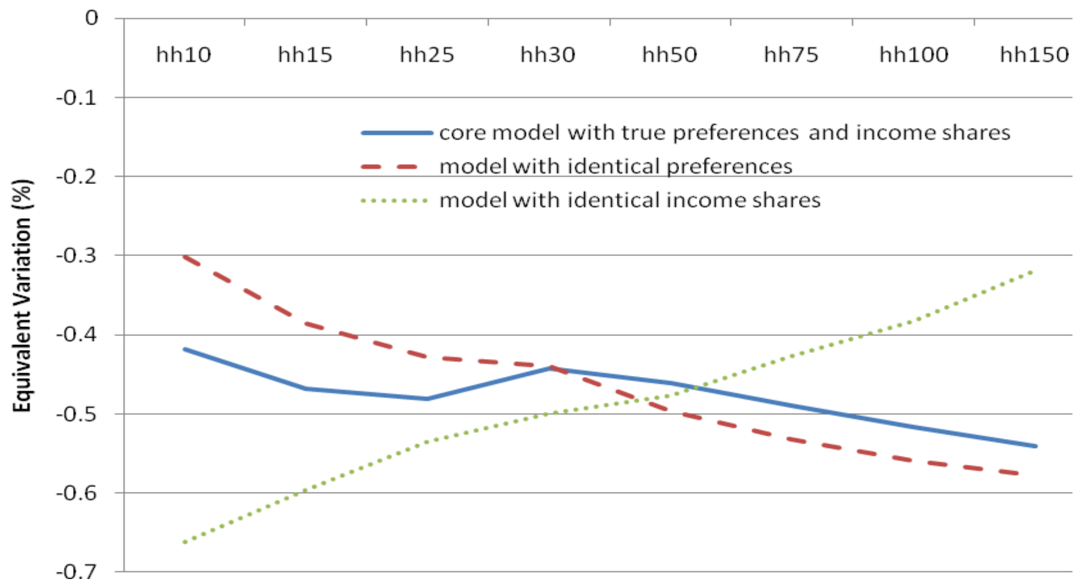

Figure 2. Decomposition of Welfare Impacts Across Income Distribution (No Revenue Recycling).

The core results we report all include distribution of the revenue in some manner. To eliminate the muddying effect of revenue distribution we conduct simulations where we do not recycle the revenue. **Figure 2** provides welfare impacts across income groups for three scenarios designed to disentangle the contribution of income and expenditure-side effects on welfare. The line labeled "core model with true preferences and income shares" corresponds to our core model based on empirically observed expenditure and income data, and shows that the carbon tax is neutral to mildly progressive especially at higher income levels. The line labeled "model with identical income shares" constructs a hypothetical case in which income shares across different income groups are equalized. As this scenario eliminates household heterogeneity on the income side, the distribution of costs is now shaped only by differences in energy expenditures across income groups. For this case, carbon pricing is distinctly regressive, consistent with previous research that has focused on the distributional implications only of energy expenditure patterns by households. Finally, the line labeled "model with identical preferences" eliminates heterogeneity in spending patterns across income groups. Hence the distribution is determined by differences in the source of income among income classes alone. In this case, the carbon tax is highly progressive.

Our analysis thus finds that in aggregate the distributional effects on carbon pricing are near neutral to slightly progressive, which differs significantly from much of the literature. This comes about through the regressive effects that occur as a result of the pattern of energy expenditure by income class that are offset by the progressive impacts on returns to labor, capital, and resources.

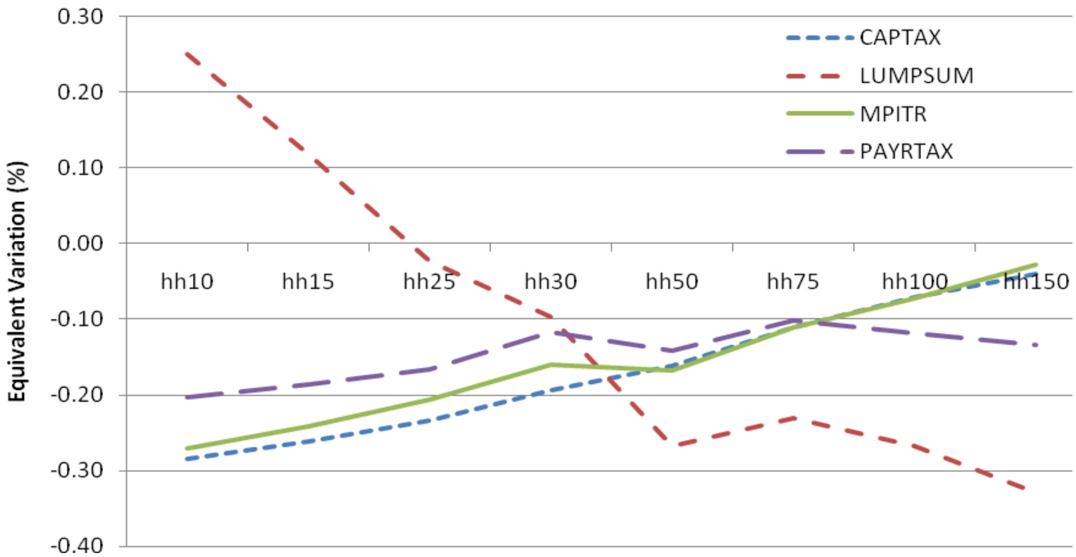

Figure 3. Welfare Impacts Across Income Distribution of Various Tax Rebates.

Also note that the estimates of welfare impact are quite large in these simulations (and larger than in the core results reported elsewhere). The larger impacts are due to the fact that revenue is not recycled to consumers but rather simply increases the government, which in our construction has no welfare benefit to the households. It is as if the revenue were thrown away. We made this assumption not to imply anything about the efficacy of government programs but only to disentangle the direct effects of carbon pricing from any plan to distribute allowances or revenue from them. In the following sections we turn back to the core results that more realistically involve different allowance revenue distributional approaches.

4.2 Distributional Effects of Carbon Pricing Across Income Groups

Our first set of results focuses on the burden of carbon pricing across household groups focusing on differences in household income. These results are most comparable to those of Burtraw *et al.* (2009) and of Hassett *et al.* (2009). We focus first on the *LUMPSUM* and tax rate reduction cases.

Figure 3 shows the *LUMPSUM* to be mildly progressive while the tax rate cases are mildly regressive. That the *LUMPSUM* is mildly progressive is not surprising and is consistent with the findings for the cap and dividend program analyzed in Burtraw *et al.* (2009). Rebating the revenue through a reduction in the payroll tax (*PAYRTAX*) allows a reduction in the payroll tax rate of 1.1 percentage points. Metcalf (2009) examined a capped payroll tax reduction and found that to be distributionally neutral over most of the income distribution, as the cap at higher income levels shifts more of the benefit to lower income households. Not surprisingly, the PAYRTAX reduction leads to the smallest costs for the low income households and produces the least regressive outcome of the tax recycling instruments analyzed here. At

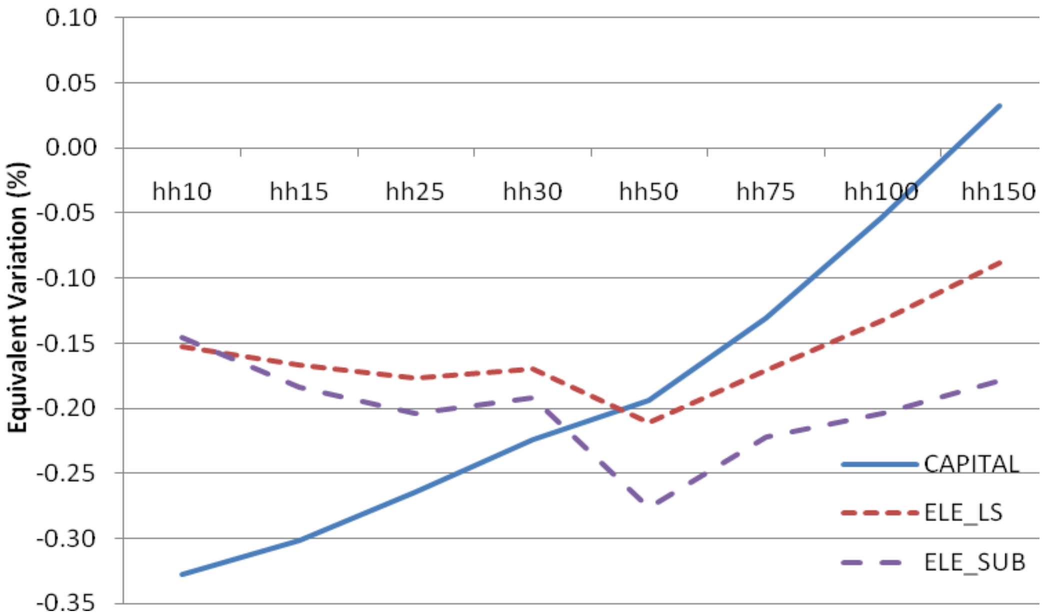

Figure 4. Welfare Impacts Across Income Distribution of Free Allocation Schemes.

incomes in the highest brackets the payroll tax limit is being exceeded and so cuts in that rate has proportionally less benefit for these income classes than does a cut in marginal personal income tax rates. The *CAPTAX* is somewhat more regressive at the lowest income levels but above hh50 mirrors closely the distributional effects of the MPITR.

The figure illustrates that the distribution of revenues significantly affect the overall progressivity or regressivity of CO_2 pricing. Carbon pricing is decidedly progressive if a *LUMPSUM* distribution of the revenue is provided. The impact on the lowest three income groups ranges from +0.25 to -0.05 percent of income. In contrast, the impact on the highest four income groups is in the range of -0.20 to -0.30 percent of income.

We next consider the distributional impact of returning the revenue based on ownership of capital. No policy explicitly proposes to do this but the free allocation of permits to covered industry groups on the basis of their emissions is equivalent to a lump sum distribution of carbon tax revenues to equity holders in these industries. Note that this is the approach that has been used for the two major cap and trade systems to date – the U.S. sulfur dioxide trading program under the Clean Air Act Amendments of 1990 and the European Union's Emission Trading Scheme for carbon dioxide.

The line marked *CAPITAL* in **Figure 4** distributes the revenue (or freely allocates permits) on the basis of capital income. Ideally we would distribute the permits on the basis of holdings in carbon intensive industries. As we do not have data on this distribution we assume that the distribution of equity holdings in carbon intensive industries is similar across income groups to the holdings of equity in general and that both can be proxied by capital income for which we do

Table 7. Equivalent Variation by Income Class (in 2006$/yr).

Income Groups	*LUMPSUM*	*PAYRTAX*	*MPITR*	*CAPTAX*	*CAPITAL*	*ELE_LS*	*ELE_SUB*
hh10	140	-114	-152	-159	-183	-85	-81
hh15	73	-115	-149	-161	-186	-103	-113
hh25	-18	-128	-159	-181	-204	-137	-157
hh30	-99	-119	-163	-197	-229	-174	-196
hh50	-305	-163	-191	-185	-222	-241	-316
hh75	-304	-133	-145	-145	-172	-224	-292
hh100	-357	-159	-97	-95	-71	-178	-273
hh150	-506	-207	-42	-61	50	-136	-276

have data.[24] The distribution based on this rebate policy is sharply regressive with welfare falling by a third of one percent for the lowest income groups while rising slightly for the highest income groups.

While we do not model H.R. 2454 here, an interesting feature of the Bill is a complex permit allocation scheme that includes allocation of permits to local distribution companies for natural gas and electricity to be used to compensate utility consumers for the higher gas and electricity prices they will face from carbon pricing. Our cases, while focusing just on electricity, illustrate how such a system may work if consumers perceive the true electricity price (*ELE_LS*) or see the allowance value rebate as effectively reducing rates (*ELE_SUB*) but note that these cases, especially other aspects of them, were not designed to represent H.R. 2454. In the *ELE_LS* scenario we model the distribution as a lump sum allocation to households proportional to their electricity consumption, while in *ELE_SUB* we cut residential rates by the amount needed to reduce the total household electricity bills by the value of allowances distributed to LDCs. We determine the number of allowances allocated to LDCs to be just that needed to cover emissions from the electricity sector—so that they need to neither buy nor sell allowances. As Figure 3 indicates this dampens the regressivity of the free allocation scenario considerably compared with the *CAPITAL* scenario.

In *ELE_SUB*, the distributional effects are dampened further so that the policy is nearer neutral, slightly penalizing households in the upper middle income range. However, all households except the lowest income level are actually worse off than in *ELE_LS*. Subsidizing the electricity prices substantially—in a few regions electricity prices are actually lower than in the no policy case—means total residential electricity consumption is higher than in *ELE_LS*. Consumers have less incentive to reduce electricity use. They face low electricity bills but someone in the economy must bear the cost of producing extra electricity. The fact that more electricity is produced raises the total cost of electricity by about $22 per household. Instead of households bearing the cost directly, it affects returns on capital, and so the cost is disproportionately borne by higher income households. Thus, *ELE_SUB* achieves a nearly

[24] This approach has been taken by, among others, Parry (2004) and Dinan and Rogers (2002) among others.

neutral or even slightly progressive result (comparing low to upper middle income households) but by making nearly all incomes groups worse off, and none substantially better off. Since we enforce tax revenue neutrality across all scenarios, the somewhat larger economic cost of the *ELE_SUB* policy lowers tax revenue and more of CO_2 revenue must be retained to offset the tax revenue loss. Thus, somewhat less of the revenue is available to be redistributed. **Table 7** shows the welfare impact of carbon pricing from the various scenarios reported in 2006 dollars per household per year. These are the same basic results in Figures 2 and 3, just reported in absolute dollar levels rather than as a share of income.

The results from this section are consistent with earlier research that assumes that the entire burden of carbon pricing is shifted forward to consumers in the form of higher prices. As shown above carbon pricing by itself is mildly progressive and the use of the revenue significantly affects the ultimate distribution. Rebates that lower marginal tax rates in general lead to a regressive result of CO_2 pricing. A lump sum distribution of the revenue that is uniform across households is progressive though other lump sum distributions can be devised (e.g. allocations to industry based on emissions) that are decidedly regressive.

While distributional impacts of carbon pricing for different income levels is of concern to policy makers, regional impacts are also of concern. We turn to an analysis of regional impact next.

4.3 Distribution of Carbon Pricing Across Regions

Different regions of the country vary in important ways that may affect the regional distribution of greenhouse gas policy impacts. **Figure 5** presents information on carbon intensity (greenhouse gas emissions per dollar of GDP) and energy intensity (energy consumption per dollar of GDP) by region.

Energy intensity varies dramatically with the South Central region of the country consuming over three times as much energy per dollar of GDP as the U.S. average while New England and New York consume roughly half the national average of energy per dollar of GDP. Variation in the intensity of greenhouse gas emissions is lower but tracks energy intensity reasonably closely.

Figure 6 presents data on electricity generation by fuel source for the various regions in the reference case scenario (no policy). Nationally over half the electricity generated comes from coal, followed by natural gas and nuclear power (19 percent each), hydropower (six percent) and refined oil (two percent).[25] The regions that rely heavily on coal and have little nuclear or hydro power have higher than average greenhouse gas intensities.

Figure 7 shows greenhouse gas emissions by region while **Figure 8** shows the percentage reduction in emissions by region for the carbon pricing policy with lump sum redistribution of revenues. **Table 8** shows total emissions in the reference scenario and the reduction following

[25] These are production estimates from the reference case of the USREP model. The model does not include non-hydro renewable electricity. In 2006 non-hydro renewable power accounted for just under 2.5 percent of electricity generation.

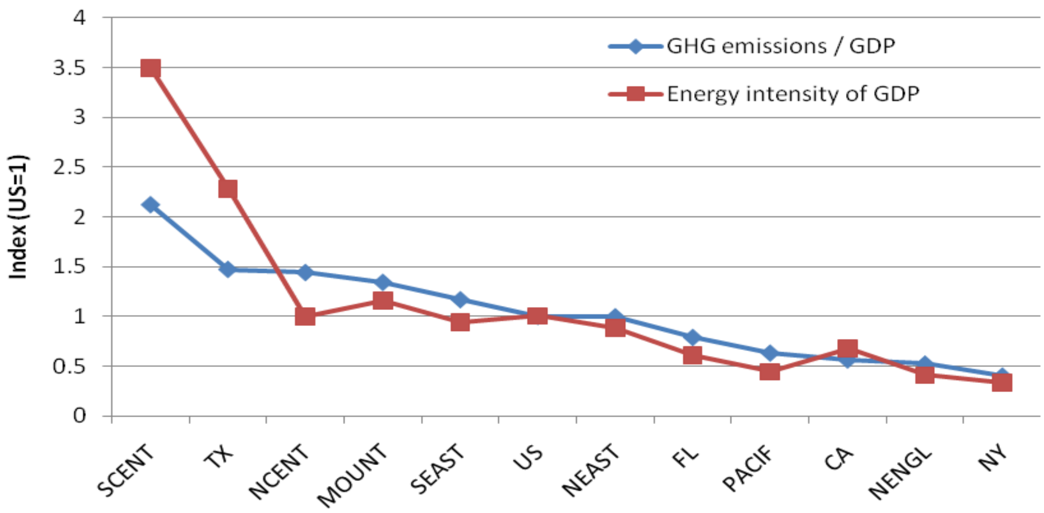

Figure 5. GHG and Energy Intensity by Region.

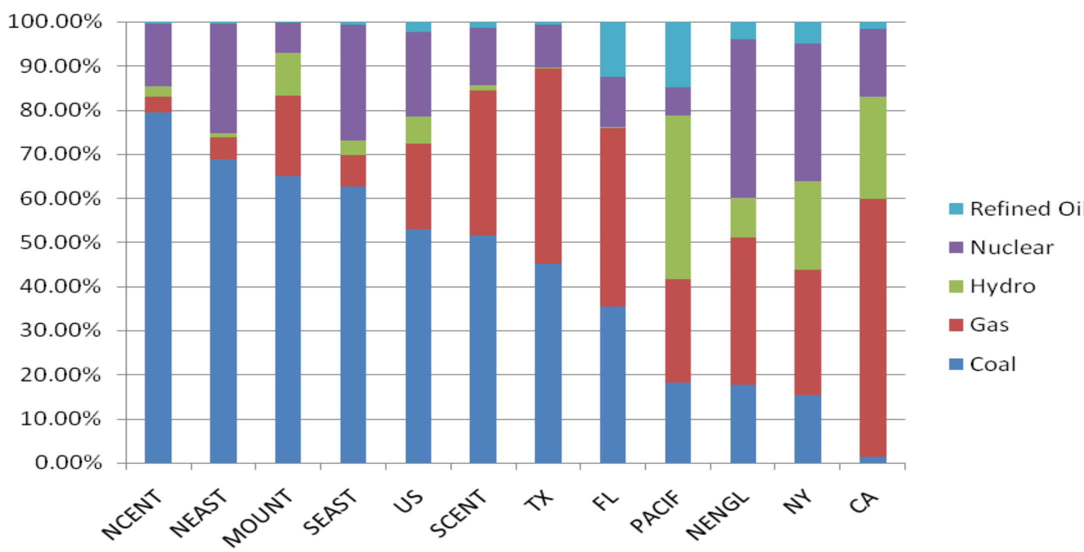

Figure 6. Regional Electricity Generation by Fuel Source.

the policy implementation. Not surprisingly regions that are carbon intensive yield a larger percentage reduction in emissions than relatively less carbon intensive regions.

An important issue that affects regional economic impacts of the policy is the ownership of capital and resources, especially those most affected by climate policy. At issue is whether resources such as coal, oil, and gas within a region are mainly owned by households in the region or whether those assets are owned equally by households across the country. The IMPLAN and Consumer Expenditure Survey data do not have detailed wealth data and no other data exist that would allow us to attribute the ownership of regional equity by region. For general equity, we assume a national pool so that households in each region own a proportion of the national pool—they do not, for example, disproportionately own equity of firms in their home region. For fossil

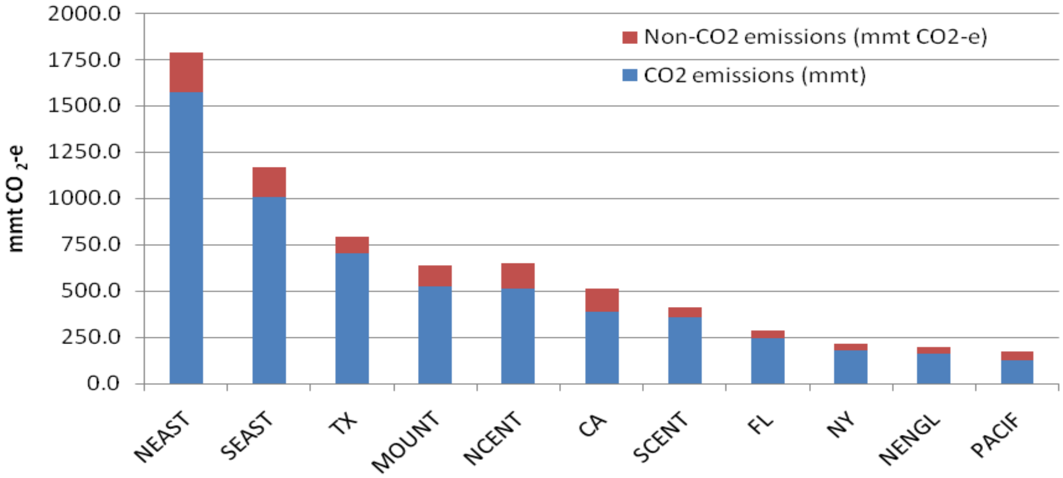

Figure 7. Greenhouse Gas Emissions in Reference Scenario.

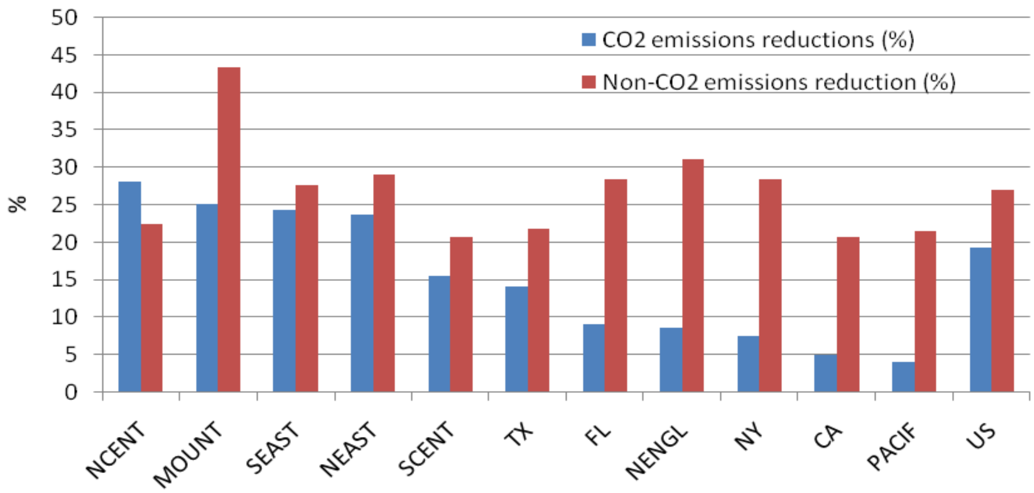

Figure 8. Reduction in Greenhouse Gas Emissions by Region.

energy resources, we have made this same assumption, and constructed an alternative polar case where all regional resources are owned within the region.[26] There is most likely a positive correlation between resource and company ownership (if for no other reason than some companies are organized as partnerships or sole proprietorships with owners living locally). Our base assumption, that resource and company ownership simply mirrors national wealth holding patterns, ignores this correlation. But many of these resources are owned by large publicly traded corporations with shares owned by investors across the country. The right answer is somewhere between these cases, and we suspect more towards to national ownership case. Thus, while the assumption that resource ownership is entirely local is extreme we construct such a scenario to show the sensitivity of results to regional ownership patterns.

[26] We assume agricultural land resources in a region are owned regionally.

Table 8. Total Emissions and Reductions by Region.

	Total Emissions	% Reduction
US	6957.7	27.3%
NEAST	1788.4	24.3%
SEAST	1168.5	24.8%
TX	794.7	15.1%
MOUNT	639.5	28.3%
NCENT	649.1	27.0%
CA	514.8	8.9%
SCENT	415.0	16.2%
FL	286.6	11.8%
NY	214.9	10.8%
NENGL	199.1	12.6%
PACIF	176.1	8.9%

Note: Emissions are in millions of metric tons of CO_2e for 2006.

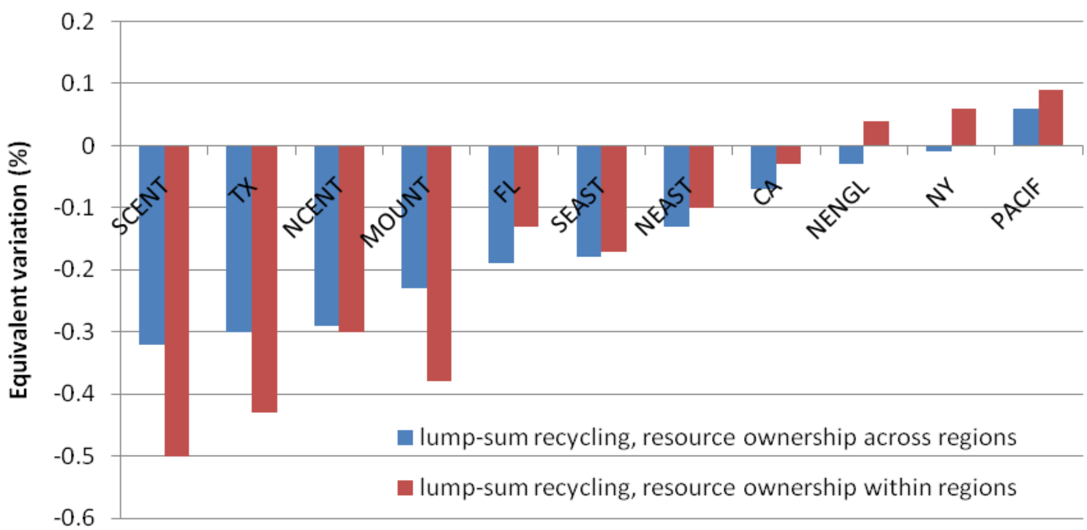

Figure 9. Welfare Impacts by Region.

Figure 9 shows the welfare impacts of the carbon pricing policy assuming lump sum recycling of the revenue under these two scenarios of energy resource (coal, oil, gas) ownership, with the national ownership case labeled "resource ownership across regions" and the other labeled "resource ownership within regions". We focus on the *LUMPSUM* scenario for examining contrasting regional resource allocation assumption scenarios. The range is from a loss of 0.3 percent to a gain of just over 0.05 percent in the "resource ownership across regions" case. This widens to a loss of 0.5 percent to a gain of almost 0.1 percent in the "resource ownership within regions" case, with those regions with significant fossil resources showing greater losses, and those without lower losses or greater gains.

Table 9. Regional Electricity Prices.

Region	Price ($/MMBTU)
NY	44.75
NENGL	39.69
CA	37.66
PACIF	32.70
FL	30.62
TX	30.52
NEAST	25.17
SCENT	22.20
SEAST	20.89
MOUNT	20.57
NCENT	19.35
US	30.15

Source: EIA SEDS. Prices are averages across end-use categories for 2006.

Table 9 shows the costs of electricity in the various regions for 2006 in the reference scenario, and comparing generation source with regional effects shows that regions with large shares of electricity generated from hydro and/or nuclear power lose little or actually gain, and those relying more on coal generated electricity bear costs. Those states with the lowest welfare costs tend to be states with higher than average electricity prices pre-policy. This suggests that prior action that reduced carbon intensity in those regions (or favorable non-fossil resource conditions) contributes to the lower costs borne by residents of those regions.[27]

Figure 10 shows regional results for the different tax recycling cases compared against the *LUMPSUM* scenario shown in the previous figure. These are the cases previously discussed for the U.S. as whole, where revenue is recycled through reductions in capital income taxes, payroll taxes or income taxes. While the differences in impacts for the various recycling approaches are quite similar at the national level (the U.S. bars), the different recycling approaches have more heterogeneity across regions. These cases tend to amplify the regional spread we saw in the *LUMPSUM* case, especially the *PAYRTAX* case. In that case, the South Central region experiences a 0.55 percent reduction in welfare, up from about 0.3 in the *LUMPSUM* case while California experiences a 0.11 percent gain, up from about a 0.05 loss. The spread rises from just over 0.3 to 0.66. The effects of the *CAPTAX* and *MPITR* are in a similar direction but less pronounced. Regions with higher incomes and, in the case of the *PAYRTAX*, a relatively larger share of the population employed, tend to benefit more from the tax recycling cases, shifting revenue to them from other states, where as the *LUMPSUM* distribution is affected directly by population.

[27] We are not suggesting that those prior actions were taken for GHG mitigation efforts. But the result of those actions has led to lower emissions and lower costs of any greenhouse gas pricing policy.

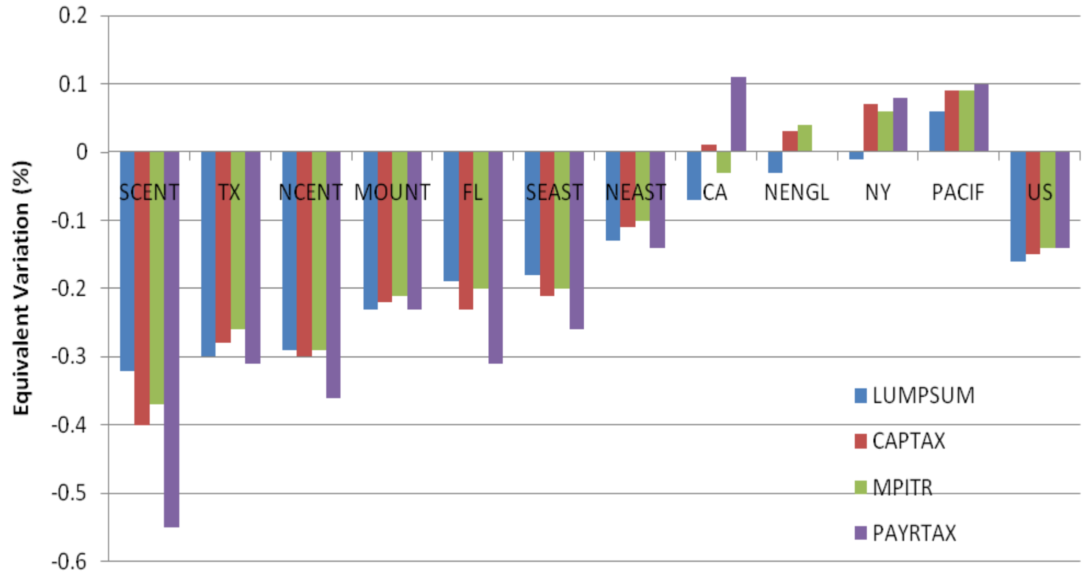

Figure 10. Welfare Impacts by Regions: Alternative Recycling Options.

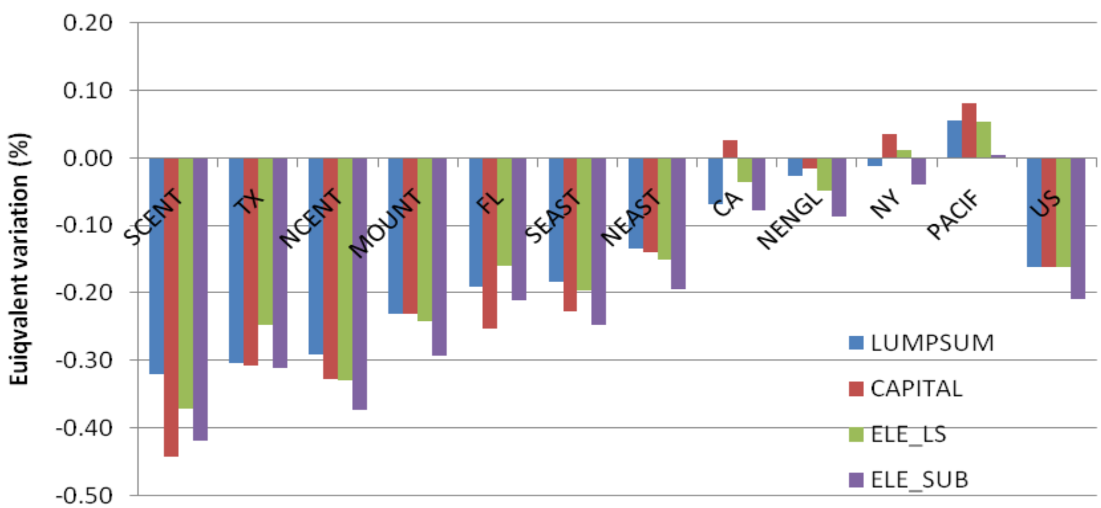

Figure 11. Free Permit Allocation: Different Allocation Methods.

The regional economic impacts we show in **Figure 11** in the free allocation scenarios are even more varied, however, some of the large differences come about because the *ELE_SUB* simply has much larger costs in all regions. In that case, the spread across regions is 0.94 percent. Free allocation to covered industries (*CAPITAL*) leads to a spread equal to 0.66 percent. The *ELE_LS* is closest to the *LUMPSUM* case with a maximal spread of 0.45. The *CAPITAL* case favors the

Table 10. Residential Electricity Price (% Change from Reference Case).

	ELE_LS	ELE_SUB
CA	8.5	-0.1
FL	9.9	1.3
MOUNT	14.8	6.1
NCENT	19.8	10.9
NEAST	14.2	5.5
NENGL	12.0	3.4
NY	7.5	-1.0
PACIF	1.6	-6.7
SCENT	12.3	3.6
SEAST	15.2	6.5
TX	8.2	-0.4
US	12.8	4.1

wealthier regions with larger ownership of capital. The ELE_LS and ELE_SUB differences from the *CAPITAL* case are driven by differences in household electricity consumption among regions as that determines allowance allocation beyond that allocated to capital. Higher income regions will tend, other things equal, to use more residential electricity, but differences in climate as it affects air conditioning and heating will also have an effect.

To further understand the effects of *ELE_SUB* and *ELE_LS* it is useful to examine the electricity price changes shown in Table 10. In *ELE_SUB* we directly allocate allowance revenue to households through reduction in electricity rates. As can be seen, in California, the Pacific region, Texas and New York electricity rates in this case actually fall compared with the no policy baseline. Florida's electricity rates rise only by 1.3%, significantly below the U.S. average. These are regions where the allocation of allowance revenue offsets more of the electricity cost rise than the U.S. average, and so they all gain in the *ELE_LS* relative to the *LUMPSUM* case.

Figures 10 and 11, by showing the U.S. average cost, also show the efficiency effects of the different revenue allocation schemes. As should be expected LUMPSUM, CAPITAL, and ELE_LS have an identical effect, and it is about -.15% of total income. The tax recycling cases reduce the cost by about 12 to 13%, with only slight differences among them. Some analyses have shown bigger gains from revenue recycling, especially when cuts are directed at capital taxation. In all cases, our assumption of revenue neutrality reduces the available revenue for recycling by about ½. Analyses of revenue recycling that did not enforce revenue neutrality assumption would be expected to thus generate twice the gain. The revenue loss is also more substantial than has sometimes been estimated. In part this stems from specification of marginal tax rates on personal income. Lower GDP has a more than proportional effect on tax revenue.

We also find the revenue loss to be sensitive to how we close international trade in the model. Lower foreign trade supply elasticities lower the revenue loss to 30 to 40% of the auction revenue. With regard to capital taxation, its greater benefit in reducing the cost of the policy is typically due to its effect over time on the growth rate of the economy. In the static model we apply here such growth effects are not captured. While our analysis is relevant to the distributional effects of these policies with long run adjustment of the capital stock to carbon pricing, to consider the full effects, especially of capital tax recycling over the longer term, requires a dynamic model that includes effects on growth. ELE_SUB raises the welfare cost from 0.15% to 0.21%, a 40% increase in the policy cost, because it introduces inefficiency in the cap and trade system.[28] That is a substantial and perhaps surprisingly large increase in the cost. However, what this scenario essentially does is to greatly reduce the incentive to conserve electricity in the residential sector, which accounts for on the order of 1/3 of U.S. electricity consumption. That has further general equilibrium effects—not only is more electricity used but it is more costly electricity because generators use more expensive lower CO_2 generation to avoid the CO_2 price. The larger economic loss, leads to lower tax revenue, and then less of the CO_2 tax revenue is available to be redistributed to households.

Lastly we consider how income heterogeneity interacts with regional heterogeneity. **Figure 12** shows differences in welfare impacts among income groups by region where revenues are returned on an equal lump sum basis to households. The broad pattern of the LUMPSUM results we saw at the national level, moderately progressive effects leading to positive income effects for the poorest households and costs for higher income households, is the same in all regions. Thus, the most important reason for differences among regions for households in a particular household income level are differences for the region that affect all households in the region. This result is fairly intuitive, if climatic conditions lead to more or less energy consumption or the regions relies more or less on carbon intensive electricity it affects all households similarly.

To better see particular differences in the distribution effects among regions we normalize each region's burden of impact for each income group by the impact on the hh30 group and show this result in **Figure 13**. In that way, we can focuses specifically on the differences in within region progressivity. The impact on households in Texas and South Central states, for example, appears to be more progressive, while Florida is the least progressive. Other states and regions fall in between these cases.

Figures 14 – 19 show the distributions across households within regions for the other scenarios that we modeled. Again, for the most part, the different recycling schemes do not produce strongly different effects in different regions with regard to progressivity or regressivity. The personal income tax, capital tax, and lump sum recycling to capital owners are generally regressive in most regions. An exception is the South Central region where most of these schemes are fairly neutral across income classes. The allocations of allowances to households based on electricity use are fairly neutral in most regions. Again, the South Central region is something of an exception where this allocation leads to a progressive result.

[28] All cases implemented a \$15/ton CO_2 price. An additional effect of reducing electricity prices is that economy-wide emissions are somewhat higher, and so the cost of achieving the same emissions level would be somewhat greater than we show here.

On balance the losses across regions by income group do not appear to differ dramatically for most revenue recycling approaches. The differences are most marked when benefits are mandated to be directed to electricity consumers and especially when those benefits are misperceived as a reduction in the price of electricity.

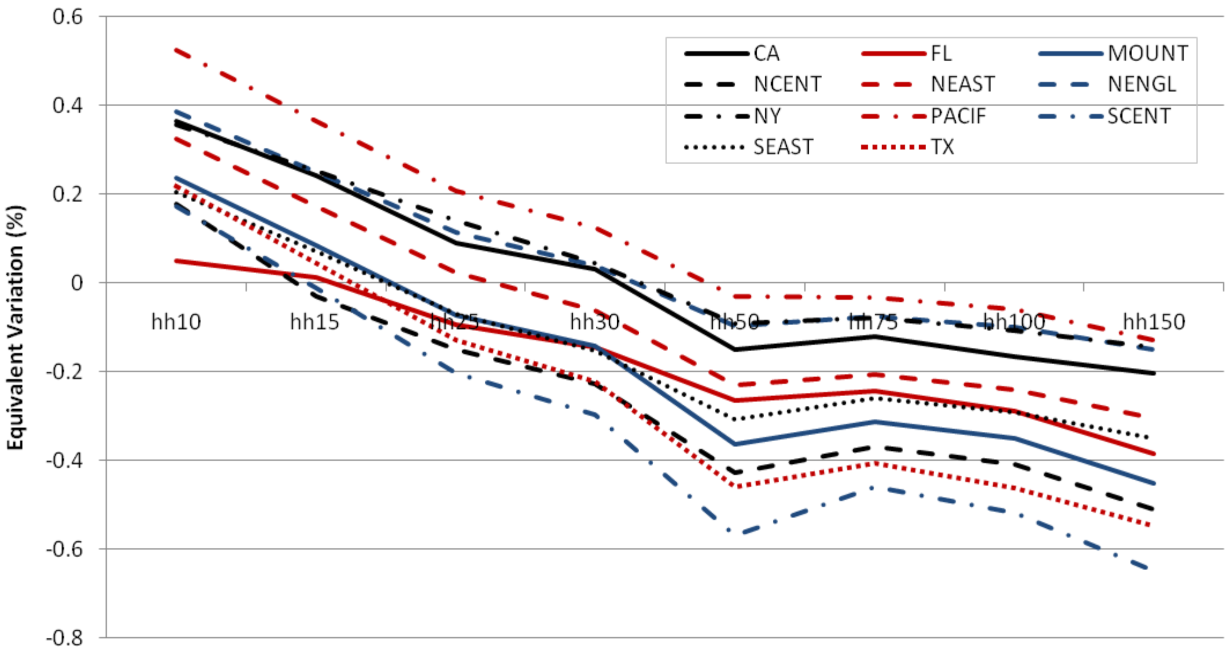

Figure 12. Income by Region Welfare Impacts.

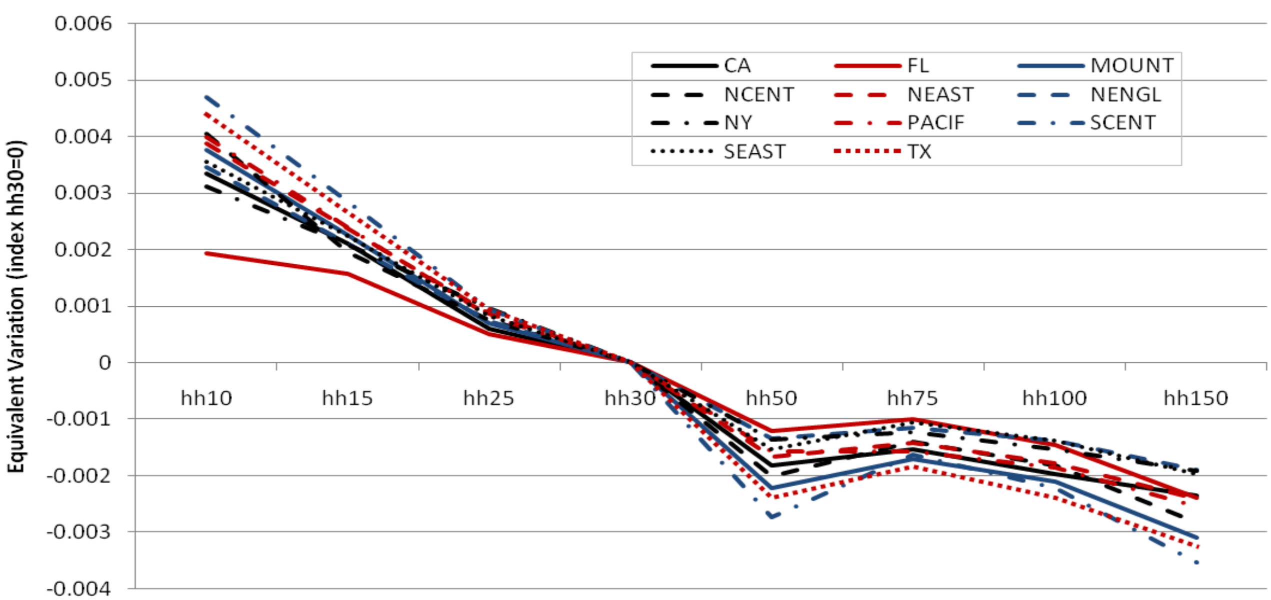

Figure 13. Normalized Income by Region Welfare Impacts.

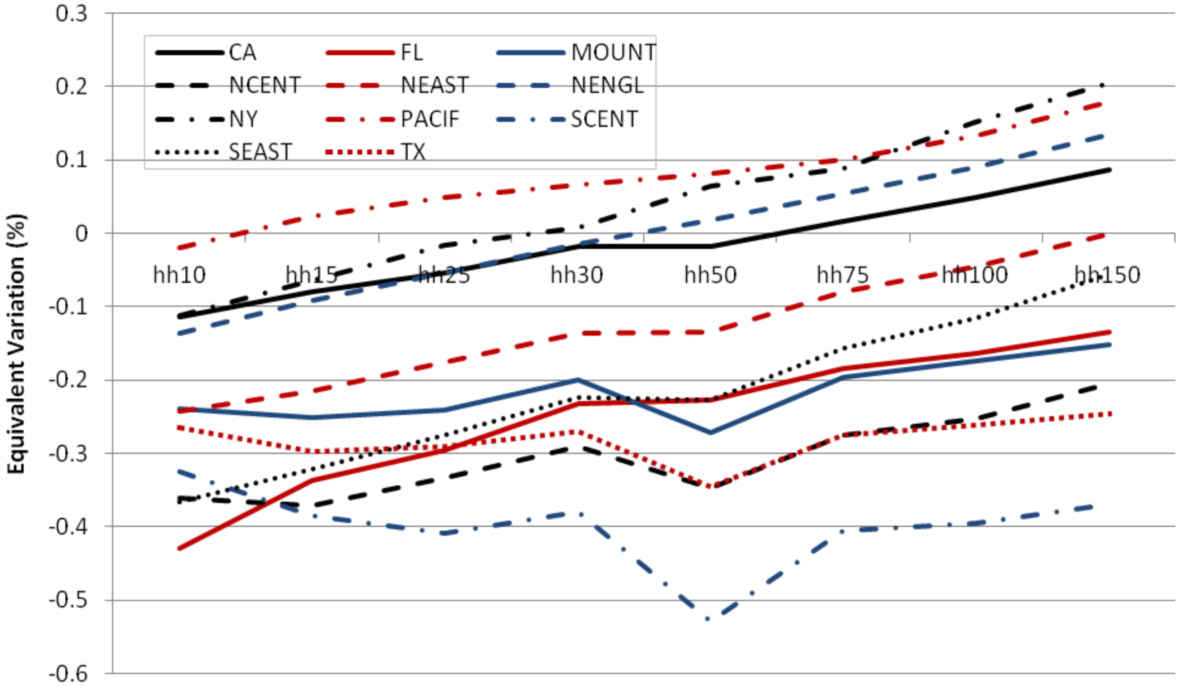

Figure 14. Income by Region Welfare Impacts: Reduction in Personal Income Tax.

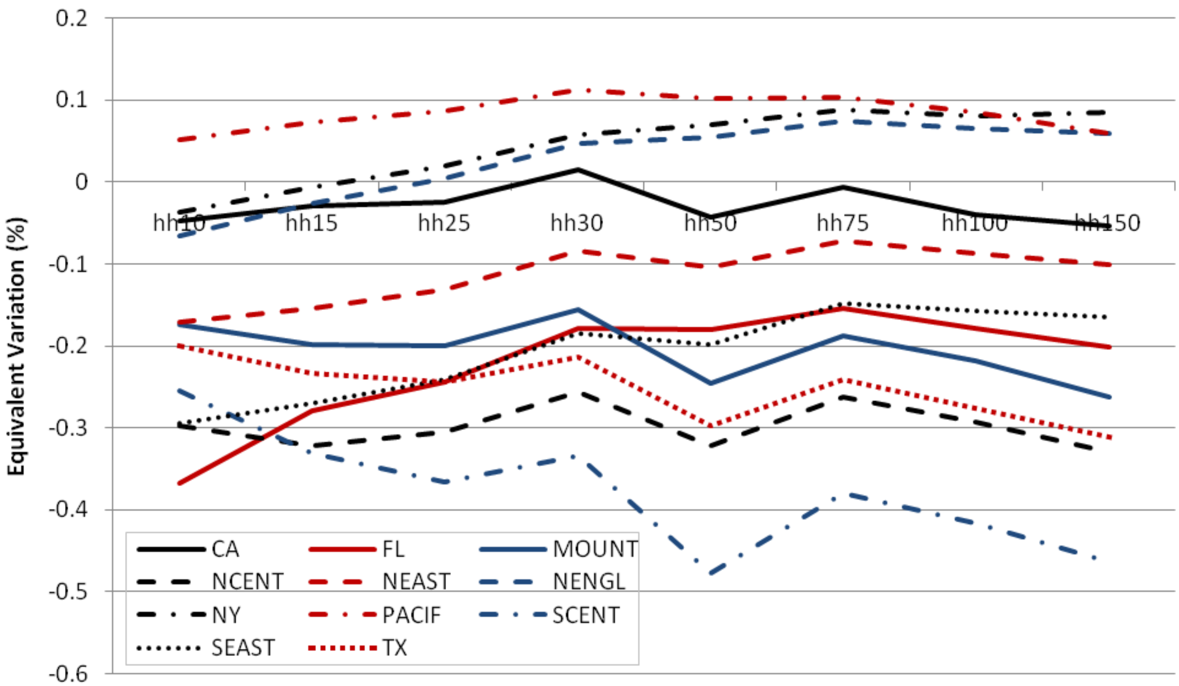

Figure 15. Income by Region Welfare Impacts: Reduction in Payroll Tax.

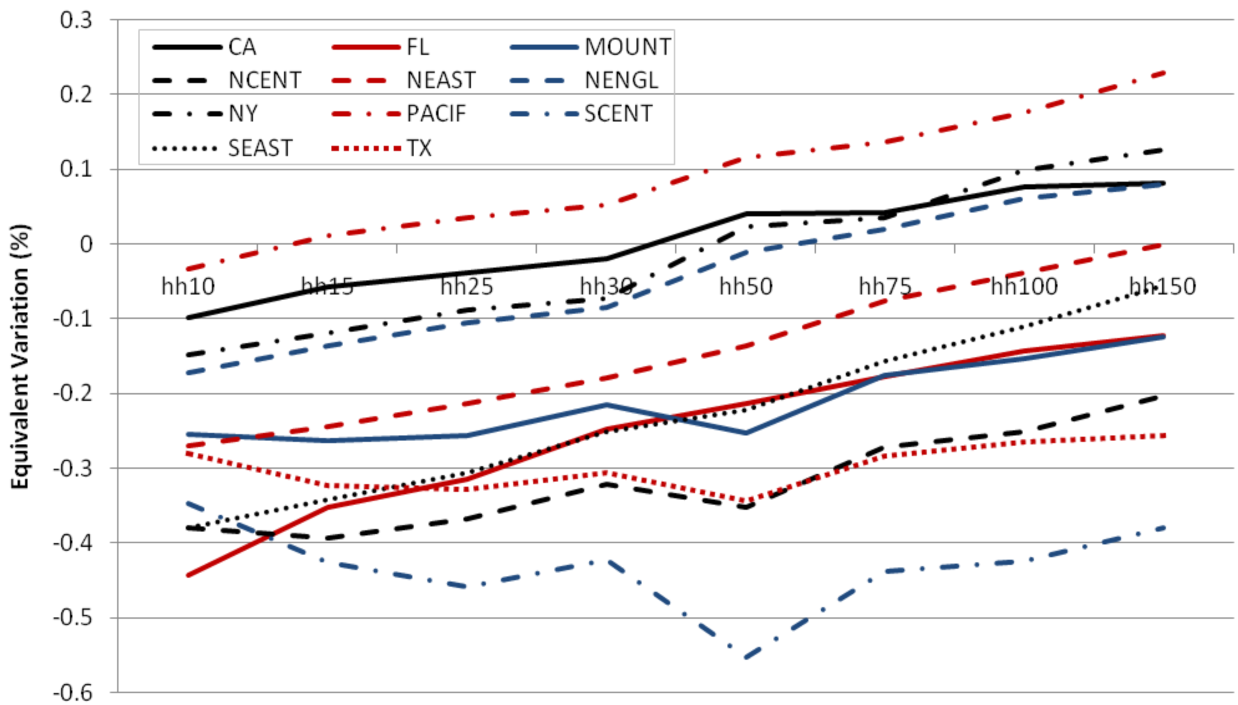

Figure 16. Income by Region Welfare Impacts: Reduction in Capital Income Tax.

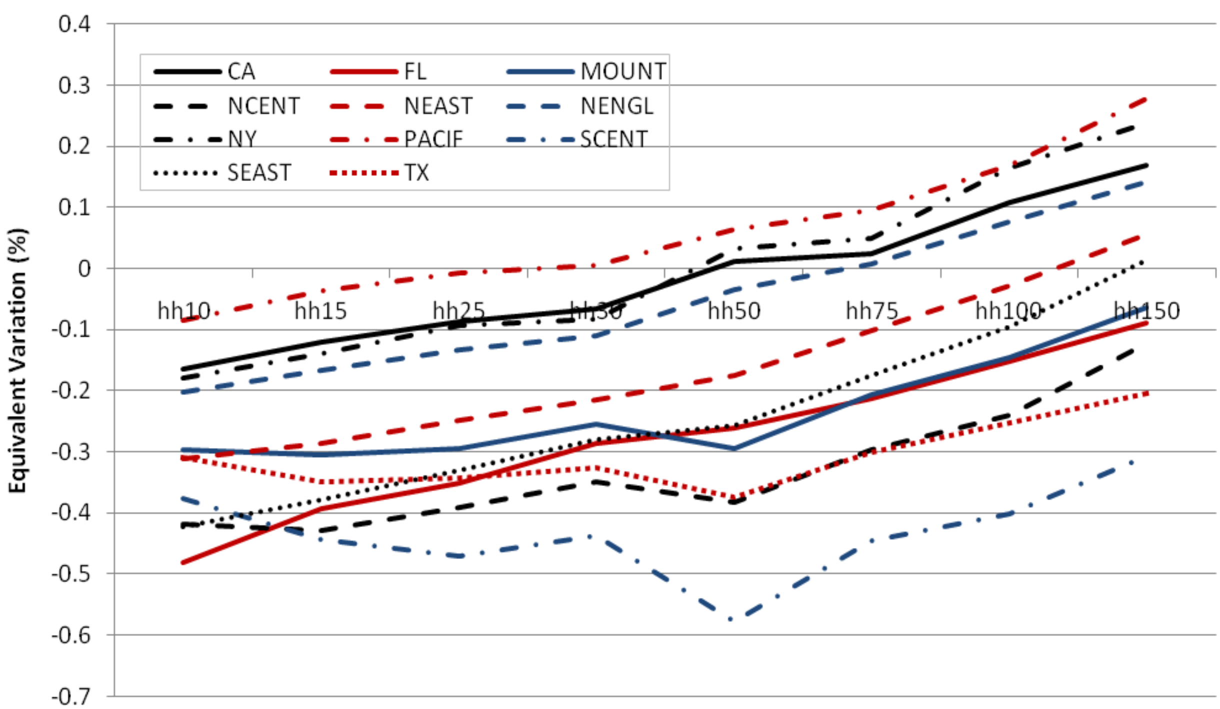

Figure 17. Income by Region Welfare Impacts: Freely Allocated Permits to Capital Owners.

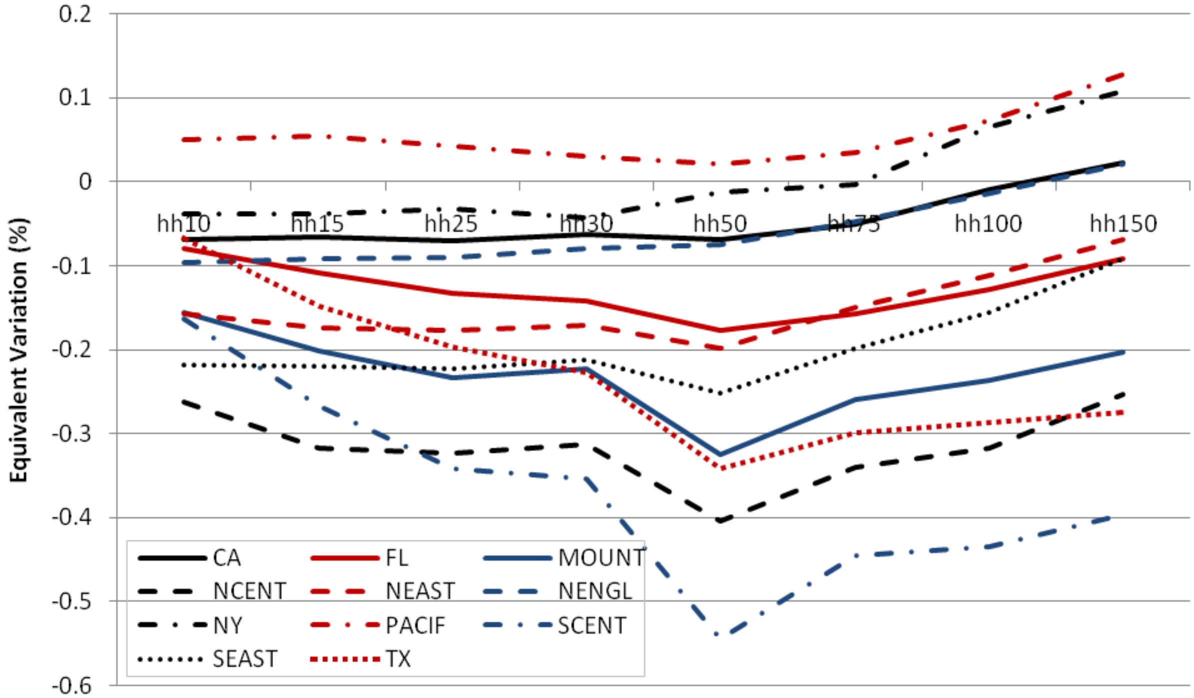

Figure 18. Income by Region Welfare Impacts: Freely Allocated Permits and Permits Directed to Electricity Consumers (Lump-sum).

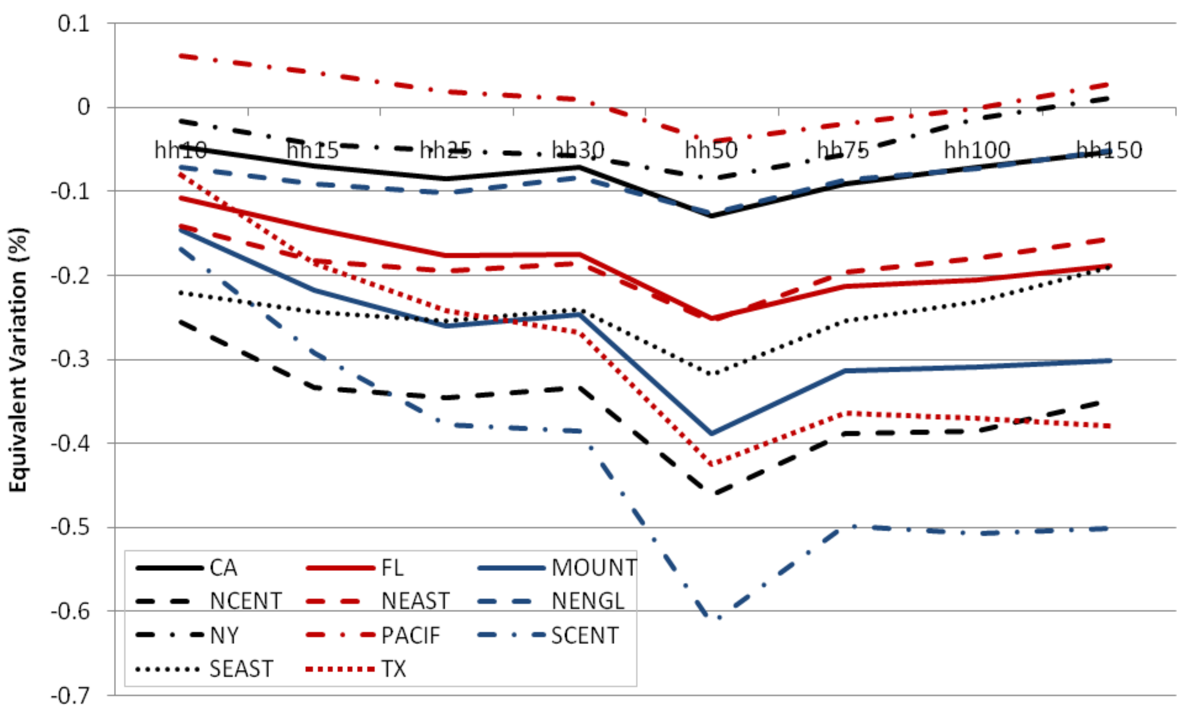

Figure 19. Income by Region Welfare Impacts: Freely Allocated Permits and Permits Directed to Electricity Consumers (Perceived as Price Reduction).

5. CONCLUSION

The USREP model was constructed with multiple regions and multiple households in each region to allow us to determine the distributional effects of a GHG mitigation policy endogenously. Past work has often used data on energy expenditure by region or household income class to estimate the cost incidence of policies based on energy cost increases. Since higher energy costs affect the cost of all goods and the policy has effects on returns to capital and resources and on wages, basing distributional effect purely on energy expenditure of different households can be misleading. In fact, we find that the income effect on distribution is progressive and completely offsets the regressive effects seen from just focusing on energy expenditure patterns.

Indeed when we focus just on the distributional impact of carbon pricing (ignoring the use of the revenue) we find that the progressive income side impacts more than outweigh the regressive spending side impacts. In other words, carbon pricing is modestly progressive. This stands in sharp contrast to earlier studies that have only focused on the spending side incidence.

In a model with a single representative household, a neutral assumption is to return auction revenue in a lump sum manner to that household. With multiple households there is no obviously neutral way to distribute allowances or revenue from auctioning them. Giving allowances away for free benefits those who receive them or who own equity in firms that get the allowances. Direct distribution of the money to households or use of the revenue to reduce other taxes all have different implications for costs borne by households of different income levels in different regions. We find that an equal lump sum household payment leads to small net benefits for low income households—the lump sum payment more than offsets costs of the policy at these income levels. Higher income households thus bear those costs. This allocation scheme was by far the most progressive one we analyzed.

While there have been a few proposals calling for an equal lump sum distribution of tax or allowance revenue from a GHG policy, most proposals have focused on more complex schemes to use this revenue. One set of proposals popular among economists focus on using the revenue to reduce other tax rates on the basis that this will reduce the distortionary effects of taxes, and thereby lower the overall cost of the policy. We examined using the revenue to reduce the payroll tax, the marginal personal income tax, and capital tax rates. We find modest efficiency gains from such revenue recycling plans, but all are regressive leading to higher percentage costs for the lowest income households. Not surprisingly the payroll tax reduction is least regressive. The relative modest efficiency gains from these appear to result from our revenue neutrality requirement. That combined with formulation of marginal personal income taxes, allows only about one-half of the revenue to be recycled as the rest must be retained to cover reduction in tax revenue.

Other proposals would give allowances away rather than cut taxes. Often, as in the European Trading Scheme or in the U.S. sulfur trading program, these are allocated to firms that would be required to turn in allowances on the basis that they "need" them. However, the incidence of mitigation cost are generally passed on to consumers or resource owners and so distributing allowances in this way leads to windfall gains for firms, and mostly benefits equity owners. In H.R. 2454, recently passed by the House but awaiting action in the Senate, a significant share of allowances are distributed to local distribution companies (LDCs) whose rates are set through public utility commissions. The presumption is that because rates are set to achieve a fair rate of return on capital, a lump sum allocation of allowances of significant value would not lead to a windfall gain for the firms, but rather that value would be returned to the ratepayer. A concern with this approach, anticipated in H.R. 2454, is that it would result in lower electricity rates and this would undermine the efficiency of the cap and trade system by reducing the incentive for consumers to adopt electricity saving measures. We did not attempt to simulate H.R. 2454 specifically, but we did structure a set of simulations that included a distribution of allowances "needed" by the LDCs to them. We returned this revenue to ratepayers either as a lump sum proportional to electricity consumption or as a reduction in electricity rates paid by households.

Among the free distribution schemes we analyzed, distribution to capital owners as would be the result if firms were given allowances was the most regressive, actually leading to benefits to the highest income households at the expense of low income households. Since lower income households spend a larger share of income on electricity (but derive a low share of income from capital returns) allocation of some of the allowances to LDCs would be expected to blunt the distributional effects. We find this case produced among the most neutral (by income) distributional results of the scenarios we considered. The simulation that reduced electricity rates did indeed undermine the efficiency of the policy, increasing costs for most households substantially compared to any other recycling policy. Thus, the language in H.R. 2454 instructing revenue to be returned to rate payers in a manner that passes through higher electricity rates is important for retaining the efficiency of the policy. In that regard, it is crucial that rate payers correctly perceive the higher rates. If a monthly bill is sent that includes an electricity charge at higher rates and reduces this by some amount of allowance value rebate, the consumer may very well just look at the bottom line bill, see not much increase, and not fully perceive that rates have gone up. We also note that with LDC distribution cases, public utility commissions could alter the distributional consequences through different formulae for distribution. Rather than distributing based on electricity consumption, they might do an equal lump sum to all households, favor lower consumption households as a proxy for directing the value to lower income households, or consider other mechanisms to distribute or use these funds. Our distributional results for this case are only illustrative of one possible way in which such revenue may be distributed. In reality, different PUCs in different regions of the country may pursue different strategies for using this allowance revenue with very different distributional implications.

Regionally we find that California, the Pacific Coast, New England, and New York generally experience the lowest cost, and even benefit from the carbon pricing policy we examined while the South Central, Texas, and Mountain States face the highest cost. Differences in costs among regions are driven by differences in CO_2 intensity of electricity production, the presence of energy producing and energy intensive industry, and income levels. Those regions that benefit do so not because abatement itself is beneficial. Abatement costs may be lower in these regions, but the reason for benefits is that the distributional scheme favors them. The regional results are relatively insensitive to the different revenue recycling approaches we explored however the lump sum approach leads to the least difference in cost among regions. All the other approaches tend to benefit higher income regions relatively more, and increase the dispersion among regions. An important bottom line result is that the amount of revenue raised, even accounting for reduction in revenue from other taxes due to reduced economic activity, is large relative to costs borne by households. As a result, the cost impact on any household is determined as much or more by how the allowances are distribution or auction revenue used than the direct cost of the policy itself.

This initial exploration of distribution impacts was conducted using a static general equilibrium model of the U.S. economy. In further work we hope to embed this model in a recursive dynamic structure to better capture investment dynamics and capital market distortions, and simulate more realistic scenarios as other future conditions change. A recursive dynamic structure will also allow us to consider scenarios that more closely approach measures laid out in H.R. 2454 or other greenhouse gas legislation proposals.

Acknowledgments

Without implication, we would like to thank Lawrence H. Goulder, Richard D. Morgenstern, Thomas F. Rutherford, and participants at the American Tax Policy Institute Conference on Energy Taxation, Washington, DC, 2009, and at the MIT Joint Program U.S. Modeling Meeting, October 2009, for helpful comments and discussion. We thank Dan Feenberg for providing data from the NBER TAXSIM simulator on marginal income tax rates. We thank Tony Smith-Grieco for excellent research assistance. We acknowledge support of MIT Joint Program on the Science and Policy of Global Change through a combination of government, industry, and foundation funding, the MIT Energy Initiative, and additional support for this work from a coalition of industrial sponsors.

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APPENDIX A. MODEL STRUCTURE

This section provides an algebraic description of the static USREP model and lays out the equilibrium conditions. Following Rutherford (1995b) and Mathiesen (1985), we formulate the equilibrium as a complementarity problem and use the GAMS/MPSGE software Rutherford (1999) and the PATH solver Dirkse and Ferris (1993) to solve for non-negative prices and quantities. Our complementarity-based solution approach distinguishes price and demand equations, market clearance conditions, budget constraints, and auxiliary equations. We use constant returns to scale elasticity of substitution (CES) and constant elasticity of transformation (CET) functions to describe production and transformation activities.

A. Behavior of Firms

In each region (indexed by the subscript *r*) and for each sector (indexed interchangeably by *i* or *j*), a representative firm chooses a level of output *y*, quantities of capital and labor, resource factors (indexed by *z*) and intermediate inputs from other sectors *j* to maximize profits subject to the constraint of its production technology. By duality and the property of linear homogeneity, optimizing behavior of the representative firm requires that:

$$p_{r,i} = c_{r,i}(pa_{r,j}, pl_r, pk, pr_z) \tag{A1}$$

where $p_{r,i}$, $pa_{r,i}$, pl_r, pk and pr_z denote prices for domestic output, intermediate inputs, labor, capital, and resource factors, respectively. $c_{r,i}$ provides a generic representation of the unit cost function for sector *i*. **Figures A1 – Figure A5** provide a schematic overview of the adopted nesting CES structure for production sectors. Zero profits conditions in (A1) exhibit complementary slackness with respect to the activity level $y_{r,i}$. For each sector, ad-valorem sector- and region-specific output tax rates, denoted by $to_{r,i}$, enter at the at the top nest. Region-specific capital income tax rates, denoted by tk_r, and payroll tax rates, denoted by tl_r, enter in the value-added nest.

To illustrate how taxes enter the CES cost functions, consider the pricing equation for the agricultural sector (Figure A2). We write the equations in *calibrated share form (*Rutherford (1995a) where ϕ's denote respective benchmark value share parameters and an upper bar refers to the benchmark value of variables. Unit cost function is given by:

$$\frac{(1-to_{r,i})\,p_{r,i}}{(1-\overline{to}_{r,i})\,\overline{p_{r,i}}} = \left[\phi_{r,i,RES} \left(\frac{p_{r,RESI}}{\overline{p}_{r,RESI}} \right)^{1-\sigma_{EVRA}} + \phi_{r,i,VA} \left(\frac{p_{r,VA}}{\overline{p}_{r,VA}} \right)^{1-\sigma_{EVRA}} \right]^{\frac{1}{1-\sigma_{EVRA}}} \tag{A2}$$

where $p_{r,RESI}$ denotes the price for the resource-intensive input bundle and the price for the value-added composite, $p_{r,VA}$, is given by:

$$\frac{p_{r,VA}}{\overline{p}_{r,VA}} = \left[\phi_{r,i,L} \left(\frac{(1+tl_r)\,pl_r}{(1+\overline{tl}_r)\,\overline{pl}_r} \right)^{1-\sigma_{VA}} + \phi_{r,i,K} \left(\frac{(1+tk_r)\,pk}{(1+\overline{tk}_r)\,\overline{pk}} \right)^{1-\sigma_{VA}} \right]^{\frac{1}{1-\sigma_{VA}}}. \tag{A3}$$

Elasticities are denoted by *σ*. Tables A1-A2 provide a list of elasticity parameters used in the model.

By Shephard's Lemma, the demand for good *j* by sector *i* is:

$$x_{r,j,i} = y_{r,i} \frac{\partial c_{r,i}}{\partial pa_{r,j}} \tag{A4}$$

and the demand for labor, capital, and resource factors is:

$$ld_{r,i} = y_{r,i} \frac{\partial c_{r,i}}{\partial pl_r} \tag{A5}$$

$$kd_{r,i} = y_{r,i} \frac{\partial c_{r,i}}{\partial pk} \tag{A6}$$

$$rd_{r,i,z} = y_{r,i} \frac{\partial c_{r,i}}{\partial pr_{r,z}}. \tag{A7}$$

B. Domestic and Foreign Trade

We adopt the Armington (1969) assumption of product heterogeneity for imports and exports. Sectoral output produced in each region is converted through a CET function into goods destined for different markets. The associated unit cost function is given by:

$$\frac{p_{r,i}}{\overline{\overline{p}}_{r,i}} = \left[\alpha_{r,i,d} \left(\frac{pd_{r,i}}{\overline{\overline{pdfx}}_{r,,i}} \right)^{1+\eta} + \alpha_{r,i,f} \left(\frac{pdfx_{r,i}}{\overline{\overline{pdfx}}_{r,,i}} \right)^{1+\eta} + \alpha_{r,i,u} \left(\frac{pdx_{r,i}}{\overline{\overline{pdx}}_{r,,i}} \right)^{1+\eta} \right]^{\frac{1}{1+\eta}} \tag{A8}$$

where $pd_{r,i}$, $pdfx_{r,i}$, and $pdx_{r,i}$ denote the price for domestic output, foreign exports, and intra-national exports, respectively, and α 's are value shares parameters. As described in the main part of the paper, we use different market structures to model intra-U.S. trade for the following three subsets of goods: non-energy goods (indexed by *ne*) are traded on a bilateral basis, electricity (indexed by *ele*) is treated as a homogenous good within the six regional pools (indexed *pool*), and non-electricity energy goods (indexed by *e*) are traded on an integrated U.S. market. In accordance with this market structure we distinguish three prices for intra-national exports:

$$pdx_{r,i} = \begin{cases} pn_{r,i} & if \quad i \in ne \\ pnn_i & if \quad i \in e \\ pe_{pool} & if \quad i \in ele \ , \ r \in pool \ . \end{cases}$$

Nested CES functions characterize the trade-off between imported (from national and international sources) and locally produced varieties of the same goods. The zero profit conditions that determines the level of Armington production, denoted by $a_{r,i}$, is given by:

$$\frac{pa_{r,i}}{\overline{\overline{pa}}_{r,i}} = \left[\beta_{r,i,d} \left(\frac{pd_{r,i}}{\overline{\overline{pd}}_{r,i}} \right)^{1-\sigma_{DM}} + \left(\beta_{r,i,u} \left(\frac{pdx_{r,i}}{\overline{\overline{pdx}}_{r,i}} \right)^{1-\sigma_{DF}} + \beta_{r,i,f} \left(\frac{pdfm_{r,i}}{\overline{\overline{pdfm}}_{r,i}} \right)^{1-\sigma_{DF}} \right)^{1-\sigma_{DM}} \right]^{\frac{1}{1-\sigma_{DM}}} \quad \text{(A9)}$$

where $pdfm_{r,i}$ and β's denotes the price for international imports and respective value share parameters, respectively.

The U.S. economy as a whole is modeled as a large open economy, i.e. we assume that world export demand and world import supply functions for each traded good are elastic implying that the U.S. can affect world market prices. Solving the model in the GAMS/MPSGE language (Rutherford, 1999) constrains us to employ constant returns to scale functions. To model concave world trade functions, for each region and sector we introduce a fixed factor which enters as an input into a Cobb-Douglas export and import transformation function. A foreign consumer is endowed with the rents from fixed factors and demands foreign exchange. Let $pfix_{r,i}$ and $pfim_{r,i}$ denote the price for the fixed factor associated with export and imports, respectively, and let pfx denote the price for foreign exchange. The pricing equation for international exports of good *i* by region *r* is then given by:

$$pfx = pdfx_{r,i}^{\gamma_{r,i}} \, pfix_{r,i}^{1-\gamma_{r,i}} . \quad \text{(A10)}$$

Note that we can calibrate to any price elasticity of foreign demand for exports using the share parameter γ.[29] If $\gamma = 1$, the U.S. cannot affect world prices, i.e. it is a small open economy.

Analogously, the pricing equation for imports from international sources is:

$$pdfm_{r,i} = pfx^{\nu_{r,i}} \, pfim_{r,i}^{1-\nu_{r,i}} \quad \text{(A11)}$$

where $pdfm_{r,i}$ and ν denote the price for international imports and a share parameter, respectively.

C. Household Behavior

In each region, a representative agent in income class h chooses consumption, residential and non-residential investment, and leisure to maximize utility subject to a budget constraint given by the level of income $M_{r,h}$. Income is defined as:

$$M_{r,h} = (pk\overline{K}_{r,h} + pl_r \overline{L}_{r,h})(1 - tinc_{r,h}) + pk\overline{RK}_{r,h} + \sum_z pr_z \overline{F}_{r,h,z} + \overline{TR}_{r,h} \quad \text{(A12)}$$

[29] To see this, consider the primal function associated with (A10): $FX = X^{\gamma} R^{1-\gamma}$, where *X* and *R* denote the quantity of goods destined for the international markets and the fixed factor, respectively. The elasticity of foreign exchange revenue with respect to the quantity exported is then given by $\gamma = \frac{X}{FX}\frac{dFX}{dX}$. Foreign exchange revenue can be written as: $FX = p(X)X$, where $p(X)$ denotes the inverse world demand function for U.S. exports. From this it follows that $\frac{dFX}{dX} = p + X\frac{dp}{dX}$, and $\frac{dFX}{dX}\frac{X}{FX} = 1 + \frac{X}{p}\frac{dp}{dX} = 1 + \frac{1}{\kappa}$, where κ denotes the inverse price elasticity of world demand for U.S. exports. Thus, we have $\gamma = 1 + \frac{1}{\kappa}$. In the small open economy case, world import demand is perfectly elastic implying $\kappa \to \infty$ and hence $\gamma = 1$.

where $\overline{K}_{r,h}$, $\overline{L}_{r,h}$, $\overline{F}_{r,h,z}$, and $\overline{RK}_{r,h}$ denote the initial endowment of non-residential capital, labor (including leisure time), fossil fuel resources, and residential capital, respectively. $tinc_{r,h}$ and $\overline{TR}_{r,h}$ denotes the region- and household specific marginal personal income tax rate and transfer income, respectively.

Preferences are represented by a CES function, and Figure A6 provides a schematic overview of the adopted nesting structure for household utility. By duality and the property of linear homogeneity, optimizing behavior of households requires that:

$$pw_{r,h} = E_{r,h}(pa_{r,i}, pl_r, pk, pinv_r) \tag{A13}$$

where $pw_{r,h}$ denotes an utility price index. $pinv_r$ denotes the price for the investment good in region r which is produced with fixed production coefficients according to:

$$\frac{pinv_r}{\overline{pinv}_r} = \sum_i \phi_{r,i,INV} \frac{pa_{r,i}}{\overline{pa}_{r,i}} . \tag{A14}$$

By Shephard's Lemma, the compensated final demand for good i by household h in region r is given by:

$$d_{r,h,i} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pa_{r,i}} \tag{A15}$$

and leisure, residential and non-residential investment demand are given by:

$$leis_{r,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pl_r} \tag{A16}$$

$$rsd_{r,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pk} \tag{A17}$$

$$nrd_{r,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pinv_r} . \tag{A18}$$

D. Government

The federal government agent demands regional government goods in fixed proportions:

$$\frac{pg}{\overline{pg}} = \sum_r \psi_r \frac{pgov_r}{\overline{pgov}_r} \tag{A19}$$

where ψ_r denotes benchmark value shares, and the regional government good is a CES aggregate of Armington goods whose price is given by:

$$\frac{pgov_r}{\overline{pgov}_r} = \left[\sum_i \xi_{r,i} \left(\frac{pa_{r,i}}{\overline{pa}_{r,i}} \right)^{1-\sigma_{GOV}} \right]^{\frac{1}{1-\sigma_{GOV}}} , \tag{A20}$$

and where $\xi_{r,i}$ denote value shares parameters. The government budget constraint is given by:

$$GOV = \sum_{r,i}(to_{r,i}\, p_{r,i} y_{r,i} + tl_r\, pl_r k_{r,k,i} + tk_r k_{r,k,i}\, pk)$$
$$+ \sum_{r,h} tinc_{r,h}\,(pl_r\,(\overline{L}_{r,h} - leis_{r,h}) + pk(\overline{K}_{r,h} - nrd_{r,h}))$$
$$- \sum_{r,h} \overline{TR}_{r,h} - \overline{BOP}. \tag{A21}$$

$\overline{BOP}$ denotes the initial balance of payments (deficit).

E. Market Clearing Conditions

The system is closed with a set of market clearance equations that determine the equilibrium prices in the different goods and factor markets. The market clearance condition for Armington goods requires that:

$$a_{r,i} = \sum_j x_{r,j,i} + \sum_h d_{r,h,i} + i_r \frac{\partial pinv_r}{\partial pa_{r,i}} + g_r \frac{\partial pgov_r}{\partial pa_{r,i}}. \tag{A22}$$

By Shephard's Lemma, the two last summands in (A22) represent the investment and government demand for good i, respectively. Regional labor markets are in equilibrium if:

$$\sum_{r,h}(\overline{L}_{r,h} - leis_{r,h}) = \sum_j ld_{r,j}\ , \tag{A23}$$

the integrated U.S. capital market clears if:

$$\sum_{r,h}(\overline{RK}_{r,h} + \overline{K}_{r,h}) = \sum_{r,j} kd_{r,j} + \sum_{r,h} rsd_{r,h}\ , \tag{A24}$$

and equilibrium on resource markets requires that:

$$\sum_{r,h} \overline{F}_{r,h,z} = \sum_{r,j} rd_{r,z,j}\ . \tag{A25}$$

Balanced intra-national trade for non-energy goods that are traded on a bilateral basis requires that:

$$y_{r,i} \frac{\partial p_{r,i}}{\partial pn_{r,i}} = \sum_{rr} a_{rr,i} \frac{\partial pa_{rr,i}}{\partial pn_{r,i}} \qquad ,\ i \in ne, \tag{A26a}$$

balanced domestic trade for non-electricity energy goods requires that:

$$\sum_r (y_{r,i} \frac{\partial p_{r,i}}{\partial pnn_i} - a_{r,i} \frac{\partial pa_{r,i}}{\partial pnn_i}) = 0 \quad ,\ i \in e, \tag{A26b}$$

and regional electricity trade is in equilibrium if:

$$\sum_{r \in pool} (y_{r,i} \frac{\partial p_{r,i}}{\partial pe_{pool}} - a_{r,i} \frac{\partial pa_{r,i}}{\partial pe_{pool}}) = 0 \quad ,\ i \in ele. \tag{A26c}$$

Foreign closure of the model is warranted through a national balance-of-payments (BOP) constraint which determines the price of foreign exchange:

$$\sum_{r,i} EX_{r,i} + \overline{BOP} = \sum_{r,i} IM_{r,i} \frac{\partial pdfm_{r,i}}{\partial pfx} \quad \text{(A27)}$$

where the level of foreign exports, $EX_{r,i}$, and foreign imports, $IM_{r,i}$, is determined by conditions (A10) and (A11).

F. Extensions of the Model for Policy Analysis

So far we have described the generic model without explicitly incorporating policy variables and other structural model features that are required for the policy analyses that we carry out in the paper. This section provides a description of how we implement GHG policies and certain model features specific to the scenarios laid out in the paper.

Following the MIT EPPA model Paltsev *et al.* (2005b), we generally introduce greenhouse gas emissions into the nest structure of each production sector as a Leontief input associated with fuel reflecting the reality that abatement involves using less of the fuel. In most other cases, we introduce greenhouse gases into a top CES nest, and the elasticities of substitution are chosen to match bottom-up estimates of abatement possibilities Hyman (2001) and Hyman *et al.* (2003).

Note that we tax energy at the point of consumption, i.e., imported coal, oil, natural gas is subject to GHG taxes as well as domestically produced energy. We tax energy associated with a process of energy (i.e., refineries), so it does not matter where energy is consumed - domestically or abroad. Finally, note that we tax energy used in production of exported goods but do not tax energy used in production of imported goods.

In our policy scenarios that consider the auctioning of permits, we impose additional constraints that determine the endogenous level of the active recycling instruments such that (i) the share of government expenditure in GDP remains constant and (ii) such that uniform transfers per household or a uniform change in terms of percentage points of the active recycling instrument are achieved. In the free allocation scenarios, we impose the constraint that the share of government expenditure in GDP is constant and we distribute the revenue (net of the portion needed to keep the share of government fixed) according to the scenario-specific allocation scheme.

In the *ELE_SUB* scenario we use the value of allowance going to the electricity sector, denoted by AV_r, to subsidize the domestic electricity consumer price, denoted by $psele_r$. We implement this by adding the following pricing equation for the electricity consumer price:

$$psele_r = pa_{r,ele} - sub_r \quad \text{(A28)}$$

where the endogenous region-specific subsidy rate, sub_r, is determined such that:

$$\sum_h sub_r d_{r,h,ele} = AV_r \quad . \quad \text{(A29)}$$

APPENDIX B. DATA SOURCES

The USREP model is built on state-level economic data from the IMPLAN dataset (Minnesota IMPLAN Group, 2008) covering all transactions among businesses, households, and government agents for the base year 2006. Aggregation and reconciliation of IMPLAN state-level economic accounts to generate a benchmark dataset which can be used for model calibration is accomplished using ancillary tools documented in Rausch and Rutherford (2009). The detailed representation of existing taxes captures the effects of tax-base erosion, and comprises sector- and region-specific ad-valorem output taxes, payroll taxes and capital income taxes. IMPLAN data has been augmented by incorporating regional tax data from the NBER tax simulator to represent marginal personal income tax rate by region and income class. The USREP model is built on energy data from the DOE EIA State Energy Data System (Energy Information Administration, 2009) comprising price and quantity data on energy production, consumption and trade. For each state, we have replaced all energy data in the economic IMPLAN dataset with assembled price-quantity EIA data and used optimization techniques to reconcile economic and energy data. The integrated dataset is *micro-consistent*, i.e. it describes a reference equilibrium, and is benchmarked to EIA energy statistics.

Additional data for the greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) emissions is based on the EPA inventory data, including endogenous costing of the abatement of non-CO_2 GHGs (Hyman *et al.* (2003)). Following the approach outlined in Paltsev *et al.* (2005b), the model incorporates supplemental physical accounts to link economic data in value terms with physical quantities on energy production, consumption and trade. Furthermore, the USREP model incorporates demographic data on the population and number of households in each region and income class based on U.S. Census Data (U.S. Census Bureau, 2006).

APPENDIX C. MODEL CALIBRATION

As customary in applied general equilibrium analysis, we use prices and quantities of the integrated economic-energy dataset for the benchmark year 2006 to calibrate the value share and level parameters in model. Exogenous elasticities determine the free parameters of the functional forms that capture production technologies and consumer preferences. Tables A1-A2 provide a list of the elasticity parameters used in the model and the respective values employed in the core scenarios. Whenever possible, we adopt the parameterization of the single U.S. region in the EPPA model (version 4, Paltsev *et al.*, 2005) for all U.S. regions which has been subject to extensive sensitivity analysis in Webster *et al.* (2002) and Cossa (2004). There are, however, a few elasticity parameters that are specific to the USREP model.

In order to parameterize capital and labor we follow the approach outlined in Babiker *et al.* (2001) to infer values for elasticities of substitution from data on related supply elasticities and benchmark shares. Based on Paltsev *et al.* (2005b) we assume that the share of leisure time relative to hours worked is 0.25. The elasticity of substitution between leisure and consumption is then calibrated to match an aggregate labor supply elasticity of 0.25 based on Babiker *et al.* (2004). We assume an uniform labor supply elasticity across regions and income groups. In a similar way we calibrate a uniform elasticity of substitution between residential and other investment to match an aggregate capital supply elasticity of 0.3, based on Chirinko *et al.* (2004). The elasticity of transformation between outputs destined for domestic and international markets is set to 2.0 for all goods. We assume a uniform price elasticity for world export demand and world import supply for all goods and regions, i.e. $\gamma_{r,i} = \nu_{r,i}$.

Table A1. Reference Values of Production Sector Substitution Elasticities

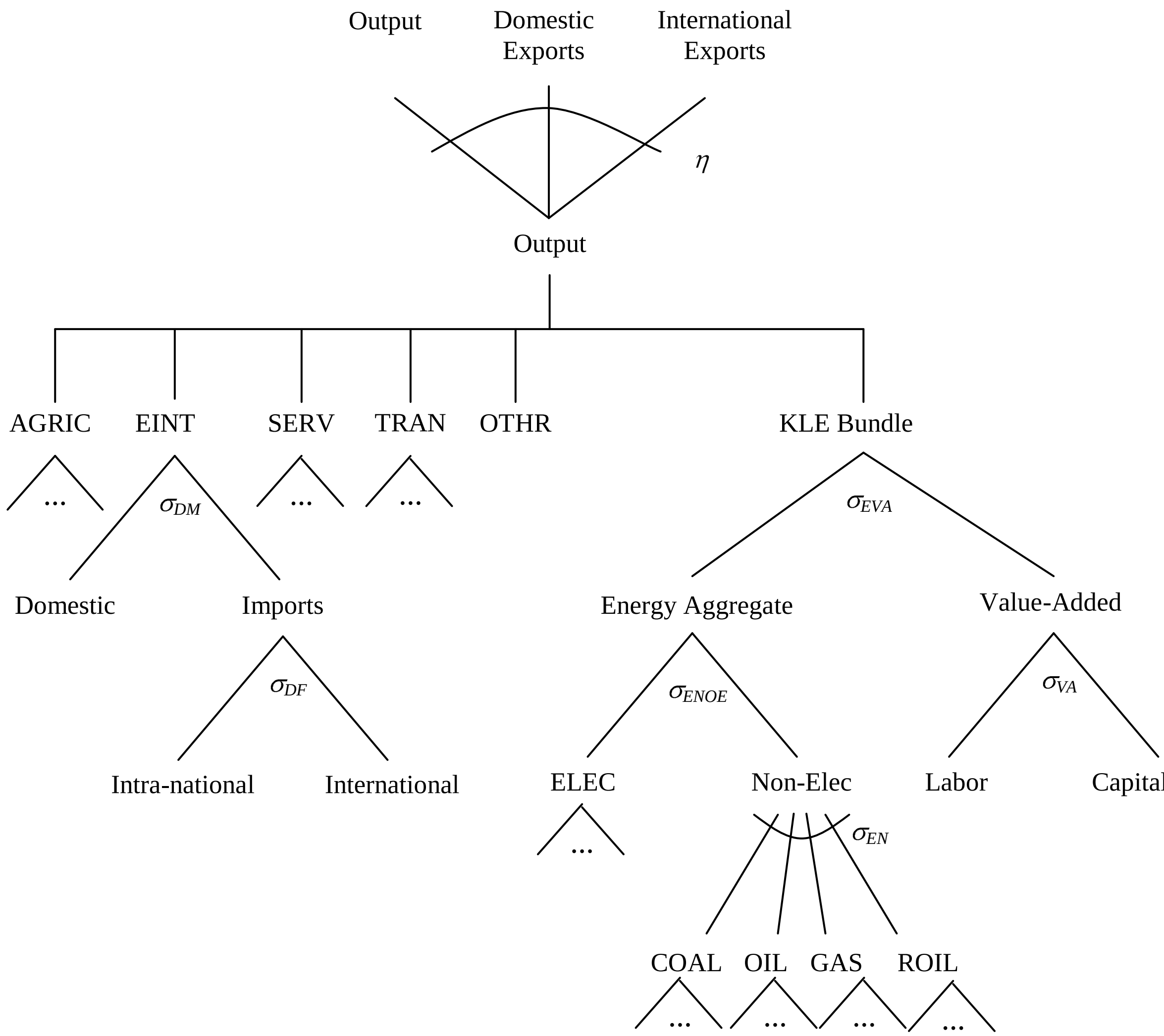
Symbol	Description	Value	Comments
Energy Substitution Elasticities			
σ_{EVA}	Energy-Value Added	0.4 - 0.5	Applies in most sectors, 0.5 in EINT, OTHR
σ_{ENOE}	Electricity-Fuels aggregate	0.5	All sectors
σ_{EN}	Among fuels	1.0	All sectors except ELEC
σ_{EVRA}	Energy/Materials/Land-Value Added	0.7	Applies only to AGRI
σ_{ER}	Energy/Materials-Land	0.6	Applies only to AGRI
σ_{AE}	Energy-Materials	0.3	Applies only to AGRI
σ_{CO}	Coal-Oil	0.3	Applies only to ELEC
σ_{COG}	Coal/Oil-Gas	1.0	Applies only to ELEC
Other Production Elasticities			
σ_{VA}	Labor-Capital	1.0	All sectors
σ_{GR}	Resource-All other inputs	0.6	Applies to OIL, COAL, GAS sectors, calibrated to match medium run supply elasticity
σ_{NGR}	Nuclear Resource-Value added	0.04-0.09	Varies by region, calibrated to match medium run supply elasticity
σ_{HGR}	Hydro Resource-Value added	0.2-0.6	Varies by region, calibrated to match medium run supply elasticity
Armington Trade Elasticities			
σ_{DM}	Domestic-Aggregated Imports	2.0-3.0 0.3	Varies by good Electricity
σ_{MM}	National Imports-Intern. Imports	5.0 4.0 6.0 0.5	Non-Energy goods Gas, Coal ROIL Electricity
η	Output produced for domestic, national, and foreign markets	2.0	Elasticity of transformation, uniform for all goods

γ, ν	Share parameters in world trade functions	0.01	Used to calibrate price elasticity of world export demand and word import supply.
σ_{GOV}	CES aggregator for government production	1.0	

Table A2. Reference Values for Final Demand Elasticities

Final Demand Elasticities for Energy			
σ_{EC}	Energy-Other Consumption	0.25	
σ_{EF}	Among Fuels and Electricity	0.4	
Other Final Demand Elasticities			
σ_{CS}	Consumption-Savings	0.0	
σ_{CL}	Consumption/Savings-Leisure	1	Calibrated to match labor supply elasticity of 0.25
σ_{SK}	Resident. Inv.-Other Investment	1	Calibrated to match capital supply elasticity of 0.3
σ_{C}	Among Non-Energy goods	0.25-0.65	
σ_{CT}	Transportation—Other Consumption	1.0	

Figure A1. Services, Transportation, Energy Intensive and Other Industries



Note: Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero. Terminal nests with … indicate the same aggregation structure for domestic and imported goods as shown in detail for the EINT sector. Goods that are traded intra-nationally are modeled as homogeneous goods. The following figures provide greater detail over the production structure for sub-sectors of the economy.

Figure A2. Agriculture

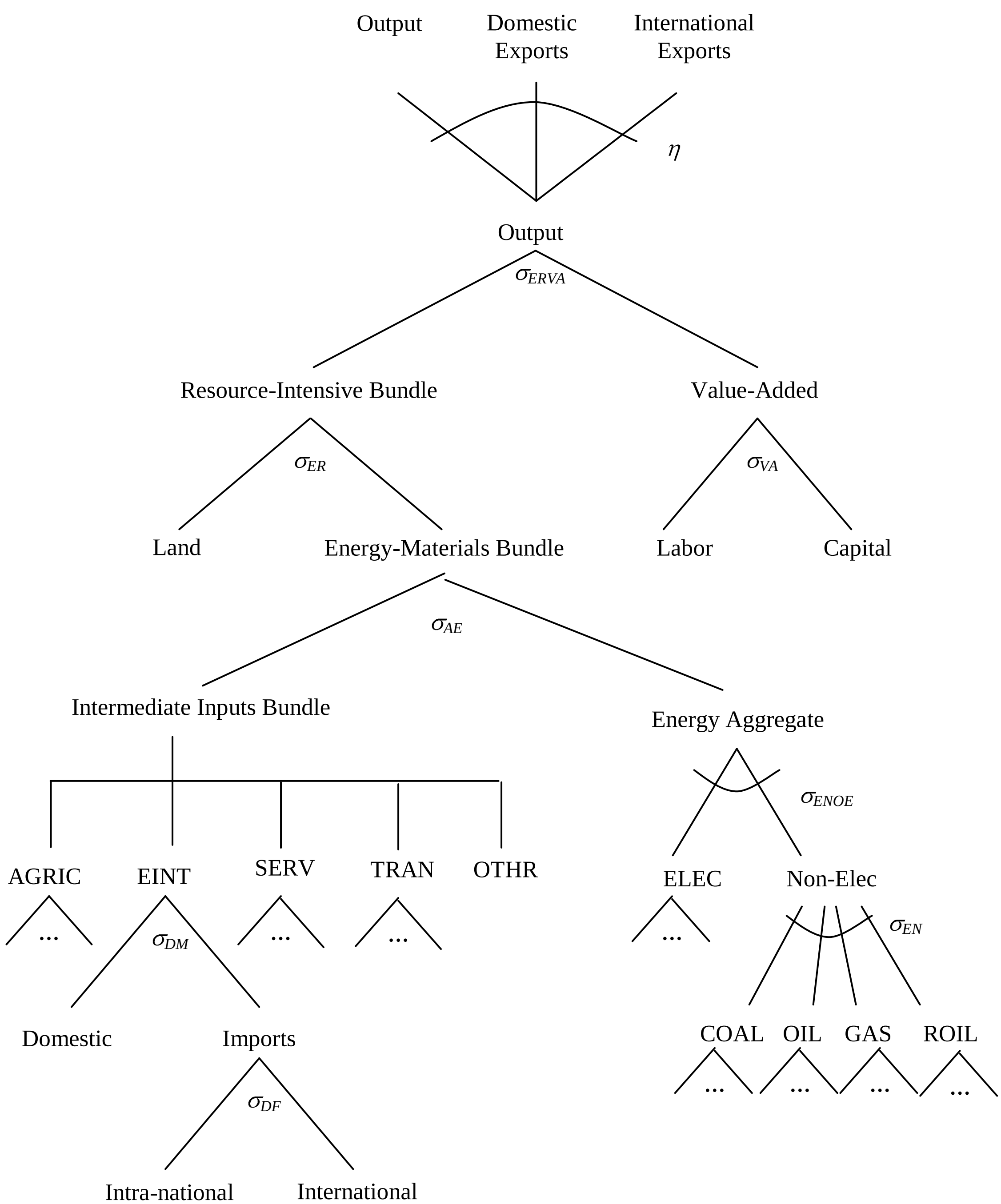


Figure A3. Electricity

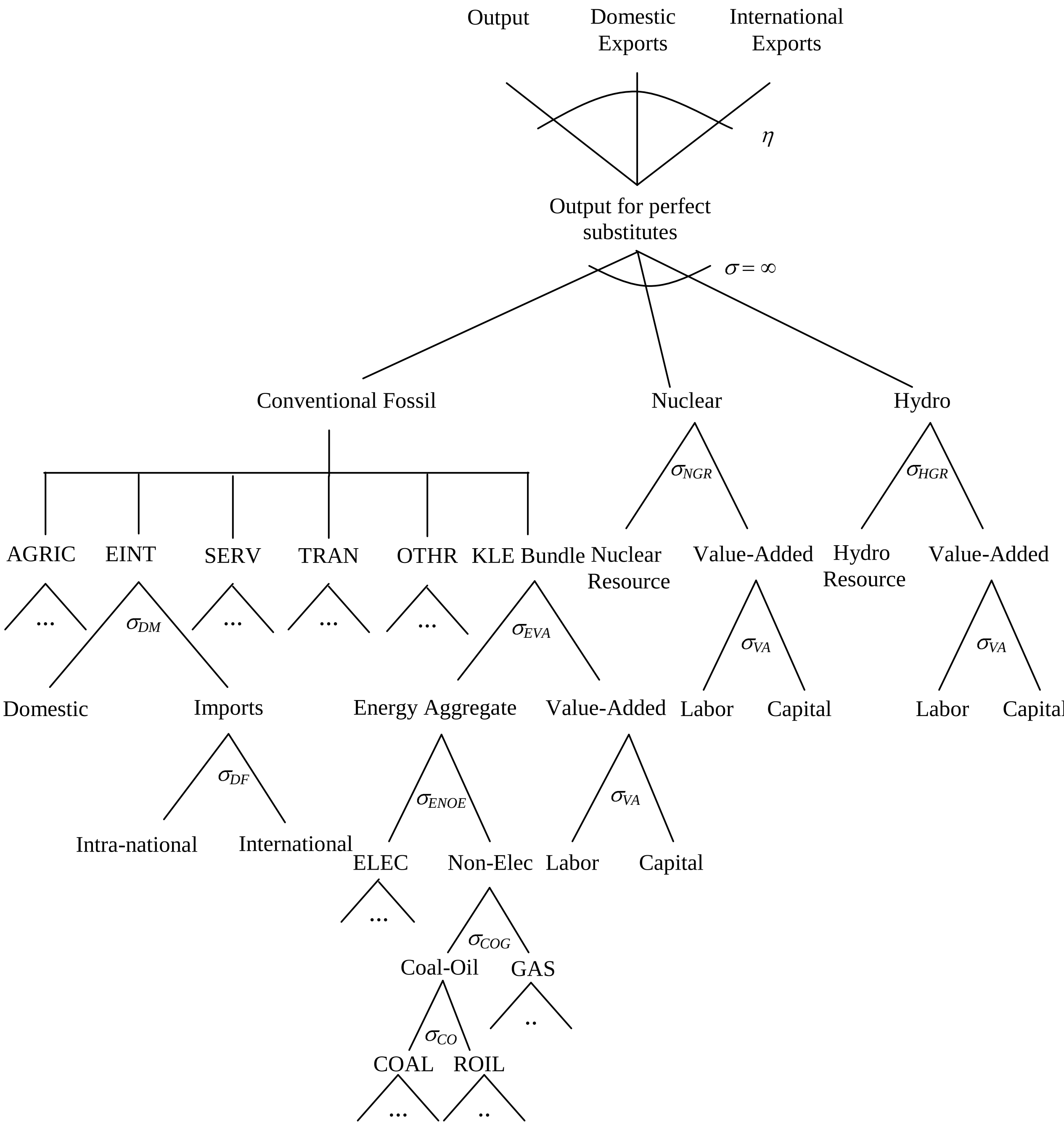


Figure A4. Primary Energy Sectors (Coal, Crude Oil, Natural Gas)

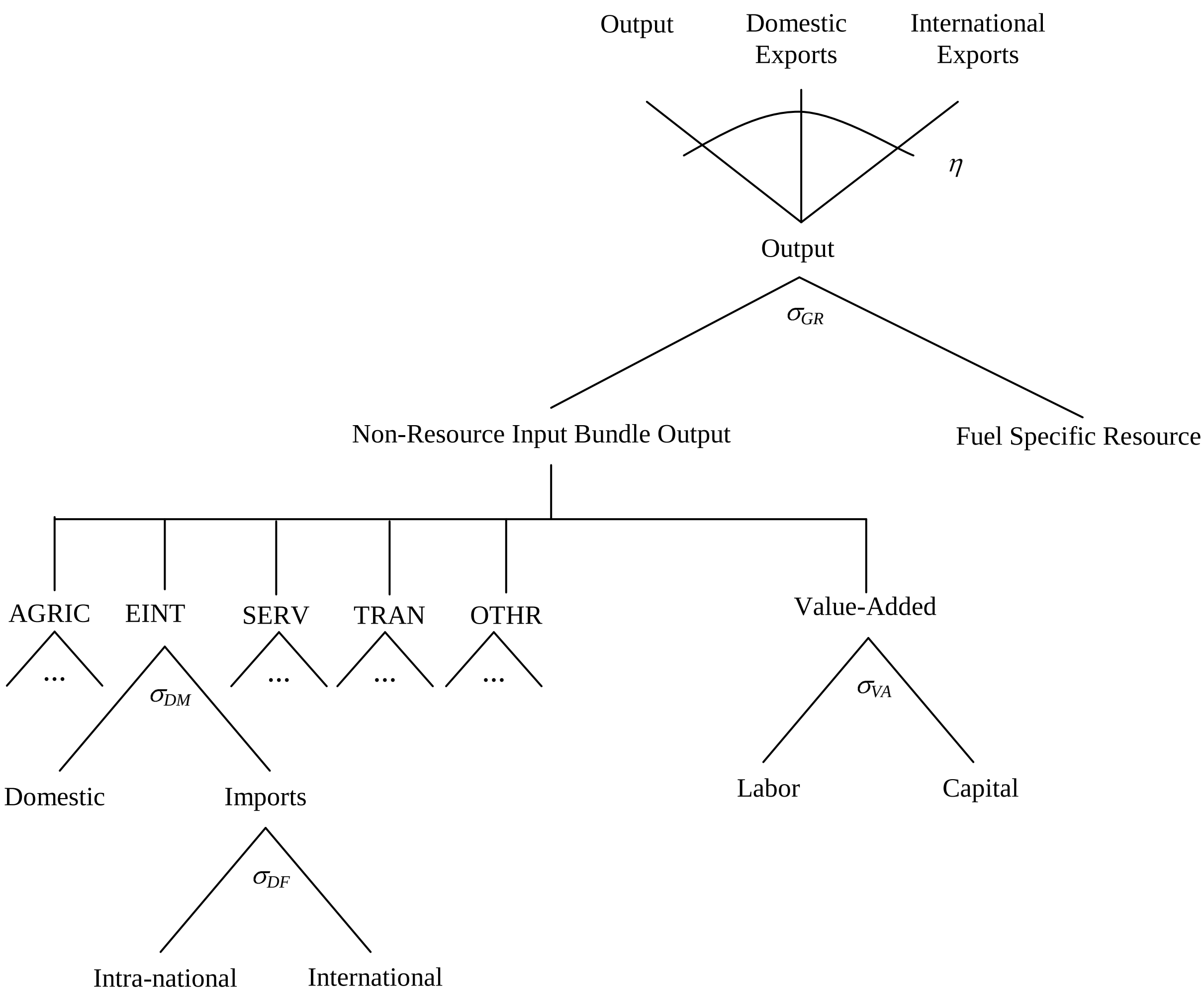


Figure A5. The Refined Oil Sector

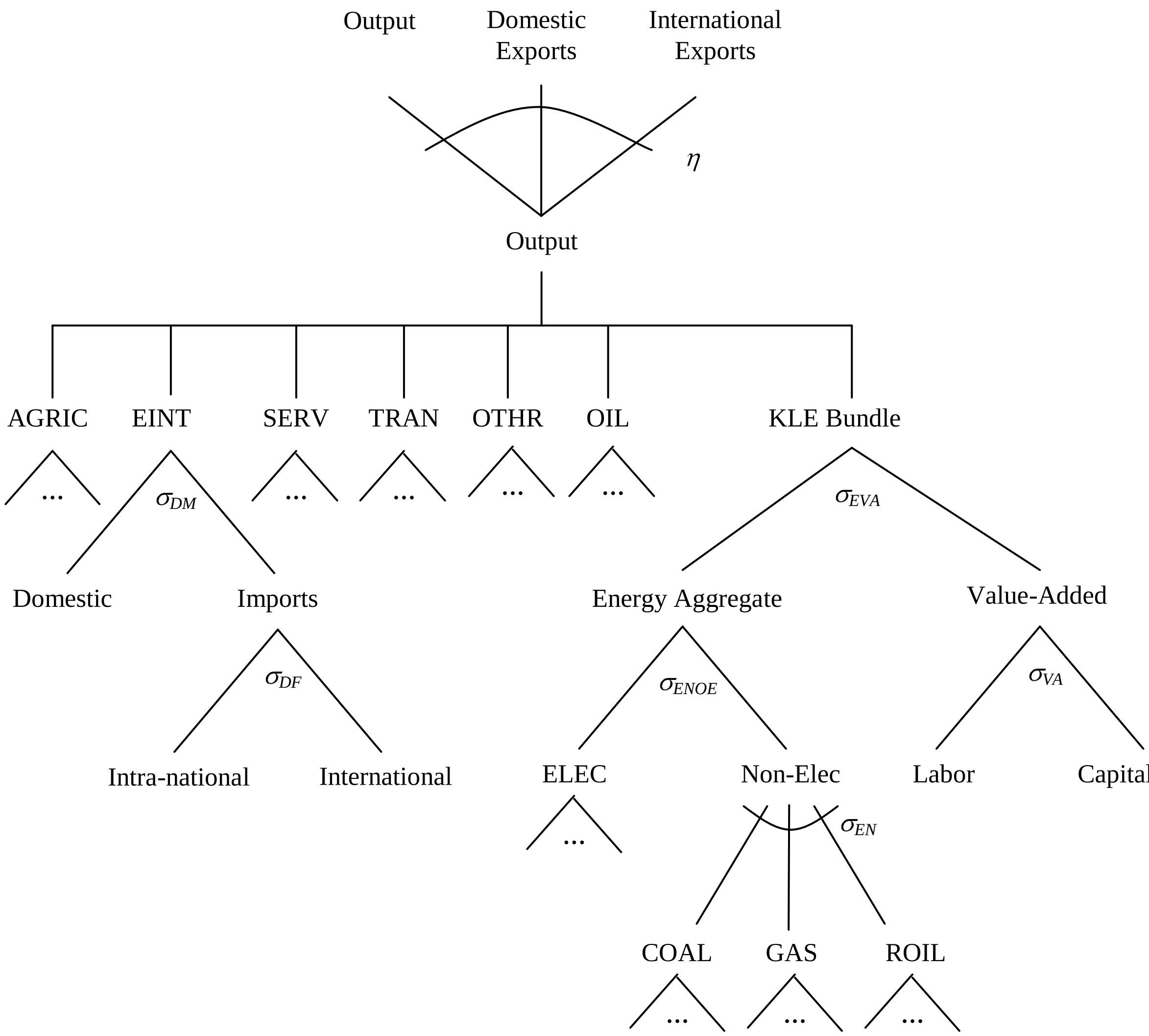
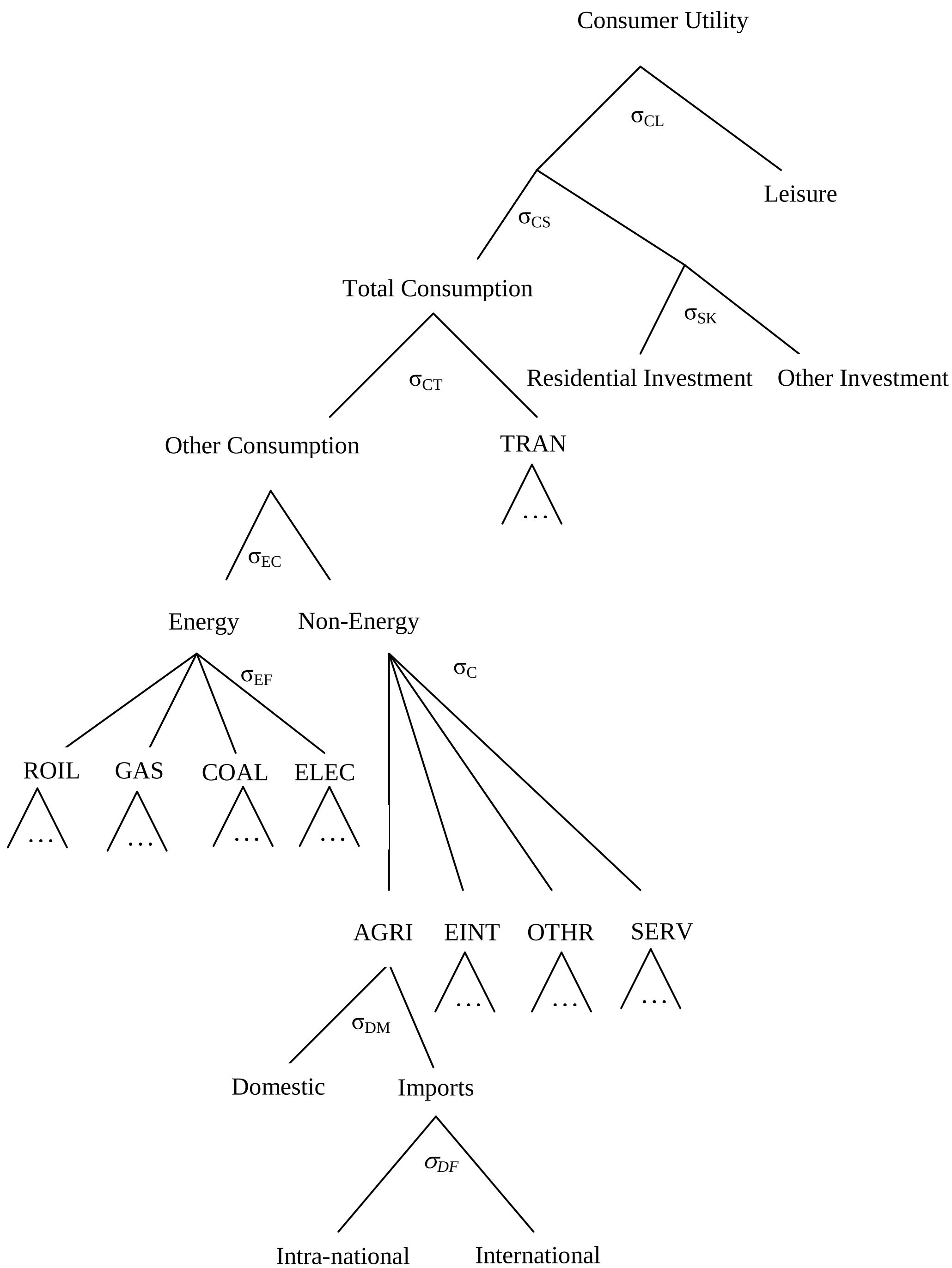


Figure A6. Household Sector



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