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Trade Effects and Emissions Leakage Associated with Carbon Pricing Policies

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ABSTRACT

In a previous work, we examined how the effects of a \$15/ton CO_2 price on U.S. industries change over four time horizons – the very short-, short-, medium-, and long-runs – as firms and consumers gradually adjust to new prices. We showed that the effects also depend on the number of countries implementing the policy as well as the use of offsetting policies, such as output-based rebates, to compensate losers. In the current extension of that work, we explore in greater depth competitiveness and emissions leakage issues – changes in trade flows and changes in emissions in countries without a carbon policy. Using a global CGE model based on GTAP 7 data, we focus on the long run effects of a multilateral carbon pricing policy, with and without output-based rebates applied to U.S. industries.

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I. Introduction

A greenhouse gas policy that puts a price on the carbon content of fossil fuels gives rise to two overarching concerns. First, energy-intensive industries that compete in global markets will be disproportionately burdened if carbon mitigation policies raise the costs of their operations relative to their unregulated international competitors. Second, some of the environmental benefits will be eroded if increases in U.S. manufacturing costs from uneven international carbon pricing cause economic activity and the corresponding greenhouse gas (GHG) emissions to 'leak' to nations with weaker, or no, GHG mitigation policies.

One way to address these competitiveness and leakage concerns is to allocate free emissions allowances or rebates to particular industries based on their output levels. This approach was proposed in the American Clean Energy and Security Act of 2009 (H.R. 2454 or Waxman-Markey) for energy-intensive trade-exposed (EITE) industries. These output-based rebates would encourage eligible firms to maintain production levels in the presence of policy-induced cost increases, while the emissions cap would sustain incentives to reduce the carbon intensity of production by creating a price on carbon. The rebates would be phased out after 2025 provided that other countries take comparable action.

Our previous paper, Adkins et al. (2010), analyzed the impact of a carbon price-cum-output subsidy policy using a framework that distinguishes the impacts over four time horizons. In the current paper we examine in greater detail the changes in trade and emission patterns across the global economy in a long run, general equilibrium setting. We consider a common carbon price across the U.S. and Annex I countries, with and without the EITE rebates for U.S. industries. We use the same global computable general equilibrium (CGE) model based on GTAP 7 data to simulate how trade, emissions, and GDP changes for each of the 8 world countries/regions (U.S., Canada, Mexico, China, India, Rest of Annex I, Oil Exporters, and Rest of World). We also examine impacts for the 29 industries in the model, including fossil fuels and energy-intensive manufactures. We further decompose emissions changes in each region according to two different methods, and decompose emissions changes for the U.S. at the industry level. Finally, we investigate the effectiveness of output-based rebates in addressing competitiveness and leakage effects.

II. Literature Review

There have been various efforts at estimating the impact of carbon prices on trade flows and emissions leakage. Some estimate this from previous studies of trade elasticities (e.g. World Bank, 2008), others estimate this by simulating global trade models (e.g. Burniaux et al., 2000; Paltsev, 2001; van der Mensbrugghe, 2009), and yet others have tried to estimate it econometrically (e.g., Aldy and Pizer, 2008). Earlier U.S. and European analyses of the industry impacts of carbon policies were reviewed in Ho et al. (2008), which used a previous version of the current modeling framework. With the passage of H.R. 2454 by the U.S. House of Representatives in 2009, a number of analyses estimating the combined effects of carbon pricing and output-based rebating have been performed, using simulation models on a quite aggregated basis. These include analyses by Fischer and Fox (2007, 2009) using their GTAP-based model; the U.S. Energy Information Administration (EIA 2009) using its NEMS model; the U.S. Environmental Protection Agency (EPA 2009a) using the ADAGE model; and an interagency U.S. government report using an updated version of the Fischer-Fox model (EPA 2009b). These studies were discussed in some detail in Adkins et al. (2010). They all find that output-based rebates are effective at reducing the output declines experienced by EITE industries.

Our previous paper (Adkins et al. 2010) was an addition to this literature. In that paper, we first examined how a unilateral carbon pricing policy on par with H.R. 2454 affected the output and profits of a detailed set of industries over the “very short run” and “short run” where the input mix was assumed to be fixed. We used an input-output framework covering 52 industries, disaggregating the most energy-intensive ones to the 6-digit level. Next we examined the “medium” and “long-run” horizons when producers can substitute away from the more expensive energy inputs; in the medium run capital was assumed fixed in each industry and in the long run all factors of production are substitutable. We used a static global CGE model with eight world regions and 29 industries. We identified the most severely affected industries and found, to some extent, that as producers are able to adapt production processes over time by substituting in less carbon intensive inputs, the output reductions were less severe. We also found that the output-based rebates can significantly offset the output losses over all four time horizons.

Several important insights have emerged from analyses that have examined trade flows and leakage effects at a more disaggregated sector level as well as emissions changes on a global level (e.g., Fischer and Fox (2007, 2009); Bohringer et al.). One is that while the rebates may be effective at reducing output losses in energy-intensive industries, they are not particularly effective at combating leakage. This is because there are different source of carbon leakage. One source of leakage is through the trade channel, in which carbon pricing policies reduce the competitiveness of energy-intensive goods by driving up their costs. This causes production of these goods, and associated emissions, to be displaced from countries undertaking the policy to non-policy countries. Another source of leakage is caused by falling world energy prices that result from decreased energy demand in policy countries, leading to increased energy consumption in non-policy countries. Output-based rebates act as a subsidy to production and can largely offset policy-induced cost increases; however, they do not address fuel price changes. Thus, rebates are not effective at addressing the second source of leakage, which has been shown to be a significant portion of overall potential leakage. In Adkins et al. (2010) we found that global leakage rates actually increased in simulations with the rebates applied to U.S. industries.

III. Model and Data

The static multi-region model discussed here defines the world economy as a collection of regional economies linked through world commodities trade. The 8 countries/regions and 29 sectors represented in the current analysis are listed in Tables 1 and 2, respectively. The regional aggregation was chosen so as to represent the U.S. and its major developed and developing country trading partners, as well as oil exporting countries. Fifteen manufacturing sectors are identified, as well as six energy sectors: coal, oil, natural gas, petroleum and coal products, electricity, and gas manufacture and distribution.

The behavior of economic agents in each regional economy is governed by neoclassical principles. On the production side, a representative firm in each sector maximizes profits by combining primary factors and intermediate goods according to a nested production structure with constant returns to scale technology. At the top nest, firms combine a value-added-energy composite with a non-energy intermediate good composite according to a constant elasticity of substitution (CES) function.[1] The composite intermediate good is in turn a fixed proportions combination of non-energy intermediate inputs. The value-added-energy composite is a CES combination of a value-added composite and an energy composite. The value-added composite is a CES combination of labor and capital, both of which are mobile across sectors but immobile internationally. The agricultural sector also includes crop land as a specific factor in the value-added nest. Similarly, the natural resource-based sectors, which include the three fossil fuels, include a specific factor that represents the resource stock. The energy composite is a CES combination of the six energy goods. On the output end, firms choose the share of their output

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[1] In the treatment of energy goods, the production structure used in this model is a simplified version of Babiker et al. (1997). Burniaux and Truong (2002) discuss the implications of alternative production structures for the overall elasticity of substitution between energy and capital, which are treated as substitutes in this model.

that will be sold on the domestic market and the share that will be exported according to a constant elasticity of transformation (CET) function.

Each regional economy has a representative household which receives income in the form of wages and returns on capital, net of factor taxes. It may also receive government transfer payments. After paying an income tax, the household divides its disposable income between consumption of goods and services and savings through an extended linear expenditure demand system (ELES). The ELES is the result of the maximization of a Stone-Geary utility function that includes leisure as an argument, subject to a full income budget constraint that includes the imputed value of time. This gives rise to a flexible household labor supply function, in which decreases (increases) in the net wage, resulting from decreases (increases) in the before-tax wage and/or increases (decreases) in the tax on labor, will reduce (increase) the amount of labor supplied.

The government in each regional economy receives income through tariffs, indirect taxes on consumption and production, and direct taxes on labor, capital, and household income. Government expenses include payments for goods and services, subsidies, and transfers. An aggregate investor in each region collects savings from enterprises (as retained earnings and depreciation allowances), households, the government, and foreigners and uses these savings to purchase investment goods. Both government and investment purchases of individual goods are made using constant expenditure shares.

World trade is represented as a set of bilateral commodities trade flows. In each region, imports arriving from different source countries are first bundled into a composite import according to an Armington specification, which treats imports from different source countries as imperfect substitutes.[2] The import composite is then bundled with a domestic version of the good, and the resulting composite good is then sold on the domestic market as both an intermediate and final good. On the export side, each region supplies exports of its transport good to an international shipping sector, which maximizes its own profits and generates "input" demand for such exports according to a CES technology. In turn, each region demands international shipping services for each exported commodity and a fixed transport cost is applied that is route- and commodity-specific. In equilibrium, total world supply of shipping services must equal total world demand.

Macroeconomic behavior in the model is specified through a simple set of rules, which together constitute the model closure. The model includes three macroeconomic balances: savings/investment, government surplus/deficit, and the balance of trade. In the current specification, for each country, total investment is fixed as a percentage of GDP, government savings are fixed at zero, and foreign savings are fixed are their base year level; thus the savings-investment balance is achieved through changes in household savings. Government purchases and transfers are also fixed as a percentage of GDP; to preserve the government revenue-expenditure balance, the tax on labor adjusts endogenously. Each country's balance of trade is fixed and changes in the exchange rate keep the external account in equilibrium. Both the exchange rate and the aggregate price level are fixed exogenously for the U.S. economy, which serves as the model's numeraire. Thus, all world prices are relative and are measured in U.S. dollars, as are trade balances.

In conducting policy analysis, the model simulates the workings of the real side of the world economy. Following a policy shock, such as the imposition of a carbon tax, prices and

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[2] The Armington assumption is commonly used in multi-region CGE models to account for two-way trade, or cross-hauling of seemingly identical goods.

quantities adjust to clear markets for products and factors within each region in the model. In addition, the model solves for a set of world prices which equate supply and demand for sectoral imports and exports across all regions. The current model is static and counterfactual simulations generate a snap-shot of the world economy, *ceteris paribus*, after the adjustment period is concluded. This post-shock equilibrium can then be compared with the initial base year equilibrium in order to calculate percentage changes in endogenous variables. The model is implemented using the General Algebraic Modeling System (GAMS) (Brooke et al., 2006).

Data and Calibration

The main economic data used to calibrate the CGE model is derived from the Global Trade Analysis Project (GTAP) database, which has become the standard database used by economists working with models of the world economy. Version 7 of the database contains comprehensive input-output and national accounting data for the year 2004 for 113 countries/regions and 57 sectors linked through detailed trade, transport, and protection data (Narayanan and Walmsley, 2008). To improve the sparsity of the database and enhance the efficiency of the solution routines, specially designed filtering and recalibration programs, adapted from Rutherford (2004), were applied to the GTAP database.

Many parameters in the model are determined through the process of calibration, which proceeds on the assumption that the base year data represents an equilibrium for the world economy. Certain parameters, in particular the elasticities associated with CES and ELES functions used in the model, must be supplied exogenously. In other words, given the functional forms chosen and the exogenously specified elasticities, remaining parameter values may be solved from the base year data. Thus chosen, model parameters will be capable of reproducing the base year data as an equilibrium solution to the model. Counterfactual scenarios may then be run, in which the calibrated model is perturbed by introducing policy shocks and then solved for alternative equilibria.

The elasticities of substitution between the individual factors in the value-added composite, between the domestic good and the import composite (Armington elasticities), and between imports from different regions were all taken from the GTAP version 7 database. So were the expenditure elasticities for composite commodities. The elasticity of substitution at the top production nest between the value-added-energy composite and the intermediate good composite was adapted from Noland et al. (1998). The elasticity of substitution between the value-added good and the energy composite, and also between energy goods within the energy nest, were adapted from Burniaux and Truong (2002). The Frisch parameter, otherwise known as the marginal utility of income with respect to income, is set uniformly across countries and was taken from Deaton and Muellbauer (1980).

Exogenously specified values for the income elasticity of labor supply are required to calibrate each region's labor supply function. Estimates of labor supply elasticities for the U.S. are much easier to come by than those for other countries. The income elasticity of labor supply for the U.S., which was also applied to the other developed countries in the model, was chosen based on Ballard et al. (2004) and de Melo and Tarr (1992). Labor supply elasticities for other countries/regions were scaled down in rough approximation with income levels, on the assumption that the poorest regions – China, India, and Rest of World – have totally inelastic labor supply responses and that other regions fall somewhere in-between these and the developed economies.

Recent versions of the GTAP database have made significant improvements in the energy data, following considerable effort to reconcile the value and trade data in the main database with energy volumes and price data from the International Energy Agency (IEA). For version 7, the 2004 IEA energy volume data has been incorporated and the energy prices have been updated to 2004 using price indices and exchange rates. CO_2 coefficients linking each country's use of the six energy goods – coal, oil, natural gas, petroleum and coal products, electricity, and gas manufacture and distribution – to CO_2 emissions were computed using combustion-based CO_2 emissions data from Lee (2008) for the 2004 base year. Lee's method accounts for the differing carbon contents of energy goods, the use of primary fuels as feed stocks, the amount of stored carbon, and other factors and is based on the Tier 1 method of the revised 1996 Intergovernmental Panel on Climate Change (IPCC) guidelines for computing national greenhouse gas inventories.

III. Effects of Policies on Output and Emissions

As in our previous paper, our analysis centers around an economy-wide carbon dioxide (CO_2) price of $15/ton. While in the previous paper we examined cases of both unilateral U.S. action and action across all Annex I economies, here we examine only the multilateral case. Assumptions about climate policies adopted in other countries are clearly important in understanding competitiveness and leakage issues. Since roughly half of US trade in energy-intensive goods involves the EU, Canada, Australia, Japan and New Zealand – nations that are reasonably expected to adopt comparable or even more stringent carbon reduction policies than the US – it is necessary to understand how such multilateral action will affect competitiveness and leakage.

One particularly significant difference between our previous and current analyses is that we have now incorporated resource supply functions into our model.[3] Work by Burniaux and Oliveira Martins (2000, 2010) and Light et al. (1999) has demonstrated the importance of assumptions about resource supply elasticities in the analysis of subglobal abatement policies, particularly in estimates of leakage. We perform sensitivity analysis on these elasticities in Appendix B.

Table 3 shows effects of the $15/ton carbon price on each region in the world economy. In the Annex I countries, the imposition of the carbon price results in a reduction in emissions on the order of 11-12%, with the largest a 12.14% reduction in the U.S. Emissions increase in all of the non-Annex I regions, with the largest increase coming from the oil exporters. The net result is a decrease in global emissions of just under 6% with a leakage rate of 6.3%.

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[3] See van der Mensbrugghe (2005) for a description of the resource supply function.

Effects of the carbon price on GDP in the Annex I countries range from -0.12% in the U.S. to -0.14 in Canada. Among the non-Annex I regions, India sees the largest increase in GDP at 0.05%. Mexico's GDP decreases by -0.16% as it is hurt by declining trade with the U.S. and a fall in the price of petroleum. The oil exporters are similarly hurt by the fall in world fossil fuel prices, with their GDP falling by -0.07%.

Table 4 shows the effects of the Annex I carbon price policy on sectoral output, trade, and use (consumption) for the aggregates of the Annex I countries, the non-Annex I countries, and the overall world economy. The percentage changes in the fossil fuel sectors are highlighted in gray, the changes in the energy intensive, trade exposed (EITE) sectors are highlighted in blue.

For the primary fossil fuels – coal, oil, and gas – the carbon price reduces overall demand, with the largest decline occurring for coal. The fall in demand is reflected in falls in both output and imports. Although falling world fossil fuel prices increase demand in non-Annex I countries, a combination of falling exports and some increase in imports leads to a decline in overall output of fossil fuels. For the world as a whole, coal use falls by 11%, oil by 2%, and gas by 5%.

For most manufactured goods, in both the Annex I and non-Annex I aggregates, the carbon price policies in the Annex I countries results in only small changes in output, consumption, and trade. An exception is the EITE sectors. In general, exports and output fall in Annex I countries, while opposite occurs in the non-Annex I countries, with the overall effect on world production a wash. A similar, though smaller effect takes place in the transportation sector.

Table 5 shows the effect of the carbon price policies on CO_2 emissions by country and fuel type. The largest effect is on coal use in the abating countries. Leakage is highest for petroleum products, where demand falls by the smallest amount (of the fossil fuels) in the Annex I countries.

IV. Decomposition of Changes in Emissions

In this section we use several decomposition methods to examine the factors that account for the change in emissions in our simulations. A frequently employed decomposition is to divide the change in emissions into scale, composition, and technique effects (Grossman and Krueger 1993; Copeland and Taylor 1994). The *scale effect* can be defined as:

$$\left[\sum_{i=1}^{n} \theta_i^{QP} \cdot Q_i^P\right] - \left[\left(\frac{\sum_{i=1}^{n} Q_i^0}{\sum_{i=1}^{n} Q_i^P}\right) \cdot \left[\sum_{i=1}^{n} \theta_i^{QP} \cdot Q_i^P\right]\right]$$

where Q_i is sectoral output and θ_i^Q is emissions per unit of output.[4] The superscript *0* denotes the initial equilibrium while *P* denotes the equilibrium that exists after the policy shock. The *scale effect* separates out the change in emissions that is related directly to the change in total output, with the technology of production and the composition of the economy held constant.

The *composition effect* can be defined as:

$$\left[\left(\frac{\sum_{i=1}^{n} Q_i^0}{\sum_{i=1}^{n} Q_i^P}\right) \cdot \left[\sum_{i=1}^{n} \theta_i^{QP} \cdot Q_i^P\right]\right] - \left[\sum_{i=1}^{n} \theta_i^{QP} \cdot Q_i^0\right]$$

With the technology of production and the scale of the economy held constant, the *composition effect* separates out the change in emissions related to the change in the mix of output following the policy shock.

The *technique effect* can be defined as:

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[4] Numerous methods of performing the scale, composition, technique decomposition exist [references]. The methodology used here involves a “path dependency” and performing the decomposition on the alternate “path” yields a slightly different result.

$$\left[\sum_{i=1}^{n} \theta_i^{QP} \cdot Q_i^0\right] \; - \; \left[\sum_{i=1}^{n} \theta_i^{Q0} \cdot Q_i^0\right]$$

With the scale and composition of the economy held constant, the *technique effect* separates out the change in emissions due to the change in the technology of sectoral production. The sum of the three separate effects equals the change in total emissions.

An alternative decomposition methodology is described in Adkins et al. (2010). The technique effect is the same (called the "input substitution effect" in the previous paper) as described above. The remaining components describe the change in emissions due to the change in domestic use (consumption):

$$\left[\sum_{i=1}^{n} \theta_i^{QP} \cdot U_i^P\right] \; - \; \left[\sum_{i=1}^{n} \theta_i^{QP} \cdot U_i^0\right]$$

exports:

$$\left[\sum_{i=1}^{n} \theta_i^{QP} \cdot X_i^P\right] \; - \; \left[\sum_{i=1}^{n} \theta_i^{QP} \cdot X_i^0\right]$$

and imports:

$$\left[\sum_{i=1}^{n} \theta_i^{QP} \cdot M_i^P\right] \; - \; \left[\sum_{i=1}^{n} \theta_i^{QP} \cdot M_i^0\right]$$

The sum of the change in emissions ascribed to the technique effect and the effects due to changes in use, exports (positive), and imports (negative) equals the total change in emissions due to the policy change.

Figure 1 shows the decomposition into technique, composition, and scale effects of the change in emissions for all countries in the model following the imposition of the carbon price in the Annex I countries. For the Annex I countries, the major source of changes in emissions comes from changes in the technology of production, i.e. fuel substitution. The change in the composition of output plays a smaller role. Following the small drop in total output in the Annex I countries, the scale effect correspondingly accounts for only a small change in emissions. Effects in the non-Annex I countries are more heterogeneous, with changes in the composition of output having a more prominent role.

Figure 2 shows the results of the second decomposition. While changes in net exports do not account for a large part of the change in emissions in the Annex I countries, they have a larger impact in the non-Annex I countries. For the oil exporters, they account for the largest share.

Unlike the technique, composition, and scale decomposition, the decomposition into technique, use, import, and export effects can be applied to individual sectors within a country. Figure 3 provides this decomposition for the U.S. Here, emissions from electricity generation are applied to the sector in which the electricity is used. As in the aggregate decomposition, the technique effect is the largest source of emission reductions. Reductions in domestic use are important for transportation and refined petroleum sectors. Although its primary CO_2 emissions are modest, due to its overall size in the economy, when the indirect emissions from electricity are included, the largest reduction in emissions can be attributed to the service sector.

V. Effects of Output-Based Rebates

H.R. 2454 provides for rebates to energy-intensive, trade-exposed industries based on their historical CO_2 emissions. Table 6 displays our estimates of the value of these allocations to EITE industries and the implied subsidy rates, computed as the ratio of the industry rebate value to the industry output value (see Appendix A.2 in Adkins et al., 2010). Of the 15 manufacturing industries represented in the CGE model, nine are eligible for subsidies, including the allocation to refining (while the refining industry is not technically eligible for the output-based rebates, the value of the grandfathered rebates granted to them also is displayed in the table). Firms within the eligible industries will be allocated quotas based on their output. The top rebate recipients are refiners ($2.02 billion); chemicals, rubber, and plastics ($1.82 billion); and iron and steel mills ($943 million). The LDC allocations for electric and gas utilities are also translated into output subsidy rates.

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Appendix A. Mathematical Model Statement

Table A1 provides a listing of the mathematical equations that define each regional economy and the linkages between them. Variables, parameters, and sets in the model are listed in Tables A2-A4. The first block of equations describes prices in the model. Equations (1) and (2) define the relationship between world prices and domestic prices; they are the f.o.b. and c.i.f. prices of traded goods, respectively. Equations (3) and (4) describe how imports arriving from different source countries are treated. They are first bundled into a composite import (according to an Armington specification), such that the composite import price is a weighted average of the source prices, inclusive of tariffs. The import composite is then bundled with a domestic version of the good, such that the resulting supply price is a weighted average of domestic and composite import prices, plus a carbon tax (for fossil fuels). The composite good is then sold on the domestic market as both an intermediate and final good. Equation (5) indicates that exports to all destinations are priced the same prior to the imposition of destination-specific export taxes and transport costs.

Equations (6) - (10) describe the three-level nested structure of production in which firms choose cost-minimizing bundles of inputs. At the top level, firms combine a value-added-energy composite and an intermediate good composite to produce sectoral output. At the second level, firms combine a value-added composite with an energy good composite to produce the value-added-energy composite, and they combine intermediate goods, inclusive of intermediate goods taxes, to produce the intermediate good composite. At the third level, firms combine factors, inclusive of factor taxes, to produce the value-added composite (with all sectors using labor and capital and a few sectors using a sector-specific natural resource), and they combine energy goods to produce the energy composite. Production technology is CES with the exception of the intermediate good composite, which is Leontief. The final price equations (11) - (13) describe factor prices net of factor taxes; the final demand price which adds a sales tax to the composite good price; and an economy-wide consumer price index, used as the price of savings.

The second block of equations are the input demand and labor supply equations. Equations (14) and (15) determine input demands for the value-added-energy composite and intermediate good composite. Equations (16), (17), and (18) determine input demands for the value-added composite, the energy composite, and the individual (non-energy) intermediate goods. Equations (19) and (20) determine input demands for individual factors and energy goods. Equation (21) is the labor supply function, which derives from maximizing an extended Stone-Geary utility function that includes leisure as an argument, subject to a full income budget constraint that includes the imputed value of time.

Final demand and trade equations are presented in the third and fourth blocks of equations. Equations (22) - (24) describe final demand functions: the extended linear expenditure system for consumer demand, in which household consumption is determined from the same utility maximization problem used to used to derive labor supply (i.e., the demand for leisure), and government and investment demands which use a Cobb-Douglas specification. Equations (25) - (27) depict the aggregation function for total domestic supply, the corresponding first order condition that determines demands for the domestically produced good and composite import, and demand for imported goods by source.

The fifth block of equations concerns the treatment of the international shipping industry. Equation (28) represents the supply of each region’s exports of the transport good to the international shipping sector, which maximizes profits and generates “input” demand for such exports according to a Cobb-Douglas technology. Equation (29) is each region’s demand for international shipping services needed for each exported commodity; a fixed transport cost is applied that is route- and commodity-specific. Equation (30) imposes an equilibrium condition in which total world supply of shipping services must equal total world demand.

Income and saving equations are presented in the sixth block. Equations (31) and (32) define household disposable income and savings. Equations (33) defines government revenue as the sum of factor taxes, intermediate input and output taxes, consumption taxes on final demand, a household income tax, taxes on imports and exports, and carbon taxes. Equations (34) - (39) list the components of revenue individually, except for the carbon tax which is explained in the seventh block. Equation (40) determines the balance of trade (foreign savings) in each region.

Carbon tax and emissions equations are presented in the seventh block. Equation (41) defines each country's fuel-specific carbon tax as the country carbon tax rate multiplied by the carbon intensity of each fuel. In equation (42), country carbon tax revenues are computed as the fuel-specific carbon tax multiplied by the total supply of each fuel (from both domestic and imported sources, which are thus taxed at the same rate). In equation (43), total country emissions are the sum of intermediate and household use of fossil fuels. Equation (44) imposes a cap on country carbon emissions as a percent of base year emissions. In this formulation, the emissions price (country carbon tax) is then determined endogenously. Alternatively, country carbon taxes may be set exogenously, with country emissions levels adjusting accordingly.

Finally, GDP, general equilibrium, and closure conditions are shown in the eighth and ninth blocks of equations. Equations (45) and (46) define real and nominal GDP, respectively, and are used in equation (47) to define the GDP deflator. Equations (48) - (51) constitute general equilibrium conditions for the model: (i) for each region, total supply of composite goods must equal total demand, (ii) factor demand must equal factor supply, (iii) firms must obey the zero profit condition, and (iv) total investment demand must equal the supply of funds available. As Walras' law is satisfied across all regions, one of the equations is redundant and may be dropped in each region. Equations (52) - (56) are closure equations that are required to make the model determinate. Gross investment, government spending, and government transfers are set as fixed shares of real GDP. Government revenue is set equal to government expenditure (government savings/deficit is set to zero). The labor tax rate shift parameter, λ_r, then acts as an equilibrating variable. Finally, the balance of world trade inclusive of shipping costs (equivalently, net foreign savings) must be zero.

Appendix B. Resource Supply Elasticities

Burniaux and Oliveira Martins (2000, 2010) and Light et al. (1999) have demonstrated the importance of assumptions about resource supply elasticities in the analysis of subglobal abatement policies, particularly in estimates of leakage. With a resource supply equation in our model following that of van der Mensbrugghe (2005), Figure B1 shows the sensitivity of the rate of leakage to the coal resource elasticity, the resource elasticity of the three fossil fuels that has the largest impact on the leakage rate. Moving from an assumption of a zero coal resource elasticity to an assumption of an elasticity equal to one reduces the rate of leakage by almost one half.

Table 1: Regions in Model

Abbreviation	Region
USA	United States
CAN	Canada
MEX	Mexico
CHN	China
IND	India
XAN	Rest of Annex I
XOI	Oil Exporters
XRW	Rest of the World

Table 2: Sectors in Model

Abbreviation	Sector
AGR	Agriculture
COA	Coal
OIL	Oil
GAS	Natural Gas
OMN	Other Minerals
FBT	Food, Beverages, and Tobacco
TEX	Textiles
WAP	Wearing Apparel and Leather Products
LUM	Wood Products
PPP	Paper Products and Publishing
PCP	Petroleum and Coal Products
CRP	Chemicals, Rubber, and Plastics
NMM	Other Non-Metallic Mineral Products
MET	Ferrous Metals (Iron and Steel)
NFM	Non-Ferrous Metals
FMP	Fabricated Metal Products
MVH	Motor Vehicles and Transport Equipment
ELE	Electronic and Communication Equipment
OME	Other Machinery and Equipment
OMF	Other Manufacturing and Recycling
ELY	Electricity
GDT	Gas Manufacture and Distribution
CNS	Construction
TRD	Trade (Retail and Wholesale Services)
TRN	Transport
CMN	Communication
FIN	Finance and Insurance
SER	Other Services
DWE	Ownership of Dwellings

Table 3: Aggregate Effects of Carbon Price Policies

Country/Region	Change in CO_2 Emissions	Change in GDP
USA	-12.14%	-0.12%
CAN	-11.67%	-0.14%
MEX	0.35%	-0.16%
CHN	0.42%	0.00%
IND	0.79%	0.05%
XAN	-11.17%	-0.12%
XOI	1.52%	-0.07%
XRW	1.21%	0.00%
Annex I	-11.60%	-0.12%
Non-Annex I	0.90%	-0.02%
World	-5.98%	-0.10%
Leakage Rate	6.30%	

Table 4: Effects of Carbon Price Policies on Sectoral Output, Trade, and Use (% Change)

	Annex I				Non-Annex I				World			
	Output	Exports	Imports	Use	Output	Exports	Imports	Use	Output	Exports	Imports	Use
AGR	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
COA	-19%	1%	-23%	-22%	-3%	-21%	4%	1%	-11%	-12%	-12%	-11%
OIL	-4%	1%	-6%	-5%	-2%	-3%	3%	2%	-2%	-3%	-3%	-2%
GAS	-7%	-2%	-11%	-9%	-4%	-12%	13%	2%	-5%	-8%	-8%	-5%
OMN	-1%	-1%	-1%	-1%	1%	0%	0%	1%	0%	0%	0%	0%
FBT	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TEX	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
WAP	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
LUM	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%
PPP	0%	-1%	0%	0%	0%	1%	-1%	0%	0%	0%	0%	0%
PCP	-7%	-11%	-2%	-7%	2%	4%	-1%	1%	-3%	-2%	-2%	-3%
CRP	-1%	-3%	1%	0%	2%	4%	-1%	0%	0%	0%	0%	0%
NMM	-1%	-3%	1%	0%	0%	3%	-2%	0%	0%	0%	0%	0%
MET	-1%	-3%	2%	-1%	1%	4%	-2%	0%	0%	0%	0%	0%
NFM	-2%	-4%	1%	-1%	2%	4%	-1%	0%	0%	0%	0%	0%
FMP	0%	-1%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%
MVH	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ELE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
OME	0%	0%	-1%	0%	0%	-1%	0%	0%	0%	0%	0%	0%
OMF	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%
ELY	-3%	-12%	6%	-3%	1%	20%	-12%	0%	-2%	-2%	-2%	-2%
GDT	-11%	-8%	-10%	-11%	1%	-6%	-3%	1%	-8%	-7%	-7%	-8%
CNS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRD	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
TRN	-1%	-3%	1%	-1%	1%	4%	-2%	0%	0%	0%	0%	0%
CMN	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%
FIN	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%
SER	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%
DWE	0%			0%	0%			0%	0%			0%

Note: Fossil fuel sectors are shaded in gray. EITE sectors are shaded in blue.

Table 5: Effects of Carbon Price Policies on CO_2 Emissions by Fuel

	Coal	Gas	Petroleum	Total
USA	-22.20%	-8.82%	-5.95%	-12.14%
CAN	-26.42%	-11.80%	-5.98%	-11.67%
MEX	0.97%	0.05%	0.48%	0.35%
CHN	0.36%	0.48%	0.63%	0.42%
IND	0.73%	0.26%	1.05%	0.79%
XAN	-20.05%	-11.64%	-5.42%	-11.17%
XOI	2.00%	2.06%	0.88%	1.52%
XRW	1.48%	1.18%	1.07%	1.21%
Annex I	-21.28%	-10.62%	-5.66%	-11.60%
Non-Annex I	0.67%	1.42%	0.89%	0.90%
World	-8.95%	-6.49%	-2.93%	-5.98%
Leakage Rate	-4.04%	-6.95%	-11.27%	-6.30%

Table 6: Permit Allocations for U.S. Industries

	Amount (mil $)	Industry output (mil $)	Subsidy rate (% of output)
Food, Beverages, and Tobacco	8.9	580,921.1	0.00%
- Food			
Textiles	3.5	57,061.5	0.01%
- Textile			
Wearing Apparel and Leather	0.0	29,184.2	-
- Apparel			
Wood	16.9	159,431.8	0.01%
- Wood and furniture			
Paper and Publishing	430.0	258,038.3	0.17%
- Pulp mills			
- Paper mills			
- Paperboard mills			
- Other papers			
Petroleum and Coal Products	2,019.9	479,059.3	0.42%
- Refining-lpg			
- Refining-other			
Chemicals, Rubber, and Plastics	1,817.7	732,146.7	0.25%
- Petrochemical manufacturing			
- Basic Inorganic Chemical Mfg			
- Other Basic Organic Chemical Mfg			
- Plastics and Material Resins			
- Artificial and Synthetic Fibers and Filaments			
- Fertilizers			
- Other Chemical & Plastics			
Non-Metallic Mineral Products	602.5	119,622.8	0.50%
- Glass containers			
- Cement			
- Lime and Gypsum			
- Mineral Wool			
- Other Nonmetallic Mineral			
Ferrous Metals	942.8	103,377.7	0.91%
- Ferrous Metal Foundries			
Nonferrous primary metals	186.5	81,780.0	0.23%
- Non-Ferrous Metal Foundries			
Fabricated Metal Products	0.0	280,007.7	-
- Fabricated Metals			
Machinery	0.0	290,442.3	-
- Machinery			
Electronic equipment	0.0	418,529.3	-
- Computer & Electrical Equipment			
Transportation Equipment	0.0	525,825.5	-
- Motor Vehicles			
- Other Transportation Equipment			
Other Manufacturing	0.0	144,487.6	-
- Miscellaneous Manufacturing			
Electric Utilities	26,933.0	372,291.2	7.23%
Gas manuf. and distribution	8,079.8	115,350.4	7.00%

Table A1: Model Equation Listing

Price Equations

$$PWE_{t,r,s} \quad = \quad (1 \ + \ te_{t,r,s}) \cdot \left(\frac{1}{ERT_r} \right) \cdot PE_{t,r} \tag{1}$$

$$PWM_{t,s,r} \quad = \quad (1 \ + \ trs_{t,s,r}) \cdot PWE_{t,s,r} \tag{2}$$

$$PM_{t,r} \cdot MX_{t,r} \quad = \quad \sum\nolimits_s \left(1 \ + \ tm_{t,s,r}\right) \cdot ERT_r \cdot PWM_{t,s,r} \cdot X_{t,s,r} \tag{3}$$

$$PX_{t,r} \cdot SX_{t,r} \quad = \quad PD_{t,r} \cdot DX_{t,r} \ + \ PM_{t,r} \cdot MX_{t,r} \ + \ CO2TAXF_{t,r} \tag{4}$$

$$PE_{t,r} \cdot EX_{t,r} \quad = \quad \sum\nolimits_s \left(\frac{1}{1 \ + \ te_{t,r,s}} \right) \cdot ERT_r \cdot PWE_{t,r,s} \cdot X_{t,r,s} \tag{5}$$

$$PTC_{t,r} \quad = \quad \left(\frac{1}{aa_{t,r}} \right) \cdot \left[\zeta_{t,r}^{\sigma^n_{t,r}} \cdot PN_{t,r}^{\left(1-\sigma^n_{t,r}\right)} \ + \ \left(1 \ - \ \zeta_{t,r}\right)^{\sigma^n_{t,r}} \cdot PVE_{t,r}^{\left(1-\sigma^n_{t,r}\right)} \right]^{\frac{1}{1-\sigma^n_{t,r}}} \tag{6}$$

$$PVE_{t,r} \quad = \quad \left(\frac{1}{ee_{t,r}} \right) \cdot \left[\eta_{t,r}^{\sigma^{ve}_{t,r}} \cdot PEN_{t,r}^{\left(1-\sigma^{ve}_{t,r}\right)} \ + \ \left(1 \ - \ \eta_{t,r}\right)^{\sigma^{ve}_{t,r}} \cdot VC_{t,r}^{\left(1-\sigma^{ve}_{t,r}\right)} \right]^{\frac{1}{1-\sigma^{ve}_{t,r}}} \tag{7}$$

$$PN_{t,r} \quad = \quad \sum\nolimits_{t6} PX_{t6,r} \cdot io_{t6,t,r} \tag{8}$$

$$VC_{t,r} \quad = \quad \left(\frac{1}{a_{t,r}} \right) \cdot \left[\sum\nolimits_f \delta_{f,t,r}^{\sigma^v_{t,r}} \cdot PF_{f,r}^{\left(1-\sigma^v_{t,r}\right)} \right]^{\frac{1}{1-\sigma^v_{t,r}}} \tag{9}$$

$$PEN_{t,r} \quad = \quad \left(\frac{1}{kk_{t,r}} \right) \cdot \left[\sum\nolimits_{t5} \kappa_{t5,t,r}^{\sigma^{en}_{t,r}} \cdot PX_{t5,r}^{\left(1-\sigma^{en}_{t,r}\right)} \right]^{\frac{1}{1-\sigma^{en}_{t,r}}} \tag{10}$$

$$PFN_{f,r} \;=\; (1 - \lambda_r \cdot tf_{f,r}) \cdot PF_{f,r} \tag{11}$$

$$PC_{t,r} \;=\; (1 + tc_{t,r}) \cdot PX_{t,r} \tag{12}$$

$$CPI_r \;=\; \frac{\sum_t PC_{t,r} \cdot C_{t,r}}{\sum_t PC0_{t,r} \cdot C_{t,r}} \tag{13}$$

Input Demand and Supply Equations

$$VE_{t,r} \;=\; \left(\frac{1}{aa_{t,r}}\right)^{1-\sigma^n_{t,r}} \cdot \left[(1 - \zeta_{t,r}) \cdot \frac{PTC_{t,r}}{PVE_{t,r}}\right]^{\sigma^n_{t,r}} \cdot Q_{t,r} \tag{14}$$

$$NX_{t,r} \;=\; \left(\frac{1}{aa_{t,r}}\right)^{1-\sigma^n_{t,r}} \cdot \left[\zeta_{t,r} \cdot \frac{PTC_{t,r}}{PN_{t,r}}\right]^{\sigma^n_{t,r}} \cdot Q_{t,r} \tag{15}$$

$$VA_{t,r} \;=\; \left(\frac{1}{ee_{t,r}}\right)^{1-\sigma^{ve}_{t,r}} \cdot \left[(1 - \eta_{t,r}) \cdot \frac{PVE_{t,r}}{VC_{t,r}}\right]^{\sigma^{ve}_{t,r}} \cdot VE_{t,r} \tag{16}$$

$$EN_{t,r} \;=\; \left(\frac{1}{ee_{t,r}}\right)^{1-\sigma^{ve}_{t,r}} \cdot \left[\eta_{t,r} \cdot \frac{PVE_{t,r}}{PEN_{t,r}}\right]^{\sigma^{ve}_{t,r}} \cdot VE_{t,r} \tag{17}$$

$$IX_{t6,t,r} \;=\; io_{t6,t,r} \cdot NX_{t,r} \tag{18}$$

$$DF_{f,t,r} \;=\; \left(\frac{1}{a_{t,r}}\right)^{1-\sigma^v_{t,r}} \cdot \left[\delta_{f,t,r} \cdot \frac{PVC_{t,r}}{PF_{f,r}}\right]^{\sigma^v_{t,r}} \cdot VA_{t,r} \tag{19}$$

$$IX_{t5,t,r} \;=\; \left(\frac{1}{kk_{t,r}}\right)^{1-\sigma^{en}_{t,r}} \cdot \left[\kappa_{t5,t,r} \cdot \frac{PEN_{t,r}}{PX_{t5,r}}\right]^{\sigma^{en}_{t,r}} \cdot EN_{t,r} \tag{20}$$

$$FS_{"lab",r} \quad = \quad MT_r \quad - \quad \left(\frac{\beta_r^0}{1 \; - \; \beta_r^0} \right) \cdot \left\lfloor \frac{SUPY_r \quad - \quad CPI_r \cdot SAV_r}{PF_{"lab",r}} \right\rfloor \tag{21}$$

Final Demand Equations

$$PC_{t,r} \cdot C_{t,r} \quad = \quad PC_{t,r} \cdot \gamma_{t,r} \quad + \quad \left(\frac{\beta_{t,r}}{1 \; - \; \beta_r^0} \right) \cdot \left[SUPY_r \quad - \quad CPI_r \cdot SAV_r \right] \tag{22}$$

$$PC_{t,r} \cdot GC_{t,r} \quad = \quad \beta_{t,r}^{GC} \cdot GPUR_r \tag{23}$$

$$PC_{t,r} \cdot ID_{t,r} \quad = \quad \beta_{t,r}^{ID} \cdot INV_r \tag{24}$$

Trade Equations

$$SX_{t,r} \quad = \quad b_{t,r} \cdot \left[\alpha_{t,r} \cdot DX_{t,r}^{\frac{\sigma_{t,r}^m - 1}{\sigma_{t,r}^m}} \quad + \quad \left(1 \; - \; \alpha_{t,r}\right) \cdot MX_{t,r}^{\frac{\sigma_{t,r}^m - 1}{\sigma_{t,r}^m}} \right]^{\frac{\sigma_{t,r}^m}{\sigma_{t,r}^m - 1}} \tag{25}$$

$$DX_{t,r} \quad = \quad MX_{t,r} \cdot \left[\frac{\alpha_{t,r}}{1 \; - \; \alpha_{t,r}} \cdot \frac{PM_{t,r}}{PD_{t,r}} \right]^{\sigma_{t,r}^m} \tag{26}$$

$$X_{t.s,r} \quad = \quad \left(\frac{1}{mu_{t,r}} \right)^{1 - \sigma_{t,r}^t} \cdot \left[ts_{t,s,r} \cdot \frac{PM_{t,r}}{\left(1 \; + \; tm_{t,s,r}\right) \cdot ERT_r \cdot PWM_{t,s,r}} \right]^{\sigma_{t,r}^t} \cdot MX_{t,r} \tag{27}$$

International Shipping Equations

$$P_{"trn",rr} \cdot TRQS_{rr} \quad = \quad ERT_{rr} \cdot its_{rr} \cdot \sum\nolimits_s \frac{P_{"trn",s}}{ERT_s} \cdot TRQS_s \tag{28}$$

$$PTR \cdot TRQD_{t,r} \quad = \quad \sum\nolimits_{s} trs_{t,r,s} \cdot PWE_{t,r,s} \cdot X_{t,r,s} \tag{29}$$

$$TRQ = \sum\nolimits_{t,r} TRQD_{t,r} \tag{30}$$

Income and Saving Equations

$$HDI_{r} \quad = \quad \sum\nolimits_{t,f} PFN_{f,r} \cdot DF_{f,t,r} \quad - \quad deprt_{r} \cdot FS_{"cap",r} \quad + \quad GTRANS_{r} \quad - \quad HTAX_{r} \tag{31}$$

$$CPI_{r} \cdot SAV_{r} \quad = \quad HDI_{r} \quad - \quad \sum\nolimits_{t} PC_{t,r} \cdot C_{t,r} \tag{32}$$

$$GREV_{r} \quad = \quad FTAX_{r} + PTAX_{r} + CTAX_{r} + HTAX_{r} + TARIFF_{r} + ETAX_{r} + CO2TAXR_{r} \tag{33}$$

$$FTAX_{r} \quad = \quad \sum\nolimits_{t} \lambda_{r} \cdot tf_{"lab",r} \cdot PF_{"lab",r} \cdot DF_{"lab",t,r} \quad + \quad \sum\nolimits_{t} tf_{"cap",r} \cdot PF_{"cap",r} \cdot DF_{"cap",t,r} \tag{34}$$

$$PTAX_{r} \quad = \quad \sum\nolimits_{t} ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r} \tag{35}$$

$$CTAX_{r} \quad = \quad \sum\nolimits_{t} tc_{t,r} \cdot PX_{t,r} \cdot \left(C_{t,r} \quad + \quad GC_{t,r} \quad + \quad ID_{t,r}\right) \tag{36}$$

$$HTAX_{r} \quad = \quad th_{r} \cdot \sum\nolimits_{f} PFN_{f,r} \cdot FS_{f,r} \tag{37}$$

$$TARIFF_{r} \quad = \quad \sum\nolimits_{t,s} ERT_{r} \cdot tm_{t,s,r} \cdot PWM_{t,s,r} \cdot X_{t,s,r} \tag{38}$$

$$ETAX_{r} \quad = \quad \sum\nolimits_{t,s} te_{t,r,s} \cdot PE_{t,r} \cdot X_{t,r,s} \tag{39}$$

$$NETINFL_{r} \quad = \quad \sum\nolimits_{t,s} PWE_{t,r,s} \cdot X_{t,r,s} \quad + \quad \left[\frac{1}{ERT_{r}}\right] \cdot P_{"trn",r} \cdot TRQS_{r} \quad - \quad \sum\nolimits_{t,s} PWM_{t,s,r} \cdot X_{t,s,r} \tag{40}$$

Carbon Tax and Emissions Equations

$$CO2TAXF_{t1,r} \quad = \quad CO2TAX_r \cdot \theta^f_{t1,r} \qquad (41)$$

$$CO2TAXR_r \quad = \quad \sum\nolimits_{t1} CO2TAXF_{t1,r} \cdot SX_{t1,r} \qquad (42)$$

$$CO2TOT_r \quad = \quad \sum\nolimits_{t1} \sum\nolimits_t \theta_{t1,t,r} \cdot io_{t1,t,r} \cdot NX_{t,r} \quad + \quad \theta_{t1,"hh",r} \cdot C_{t1,r} \qquad (43)$$

$$CO2TOT_r \quad = \quad cap_r \cdot CO20_r \qquad (44)$$

GDP Equations

$$GDPR_r \quad = \quad \sum\nolimits_t PC_{t,r} \cdot \left(C_{t,r} + GC_{t,r} + ID_{t,r} \right) \quad + \quad ERT_r \cdot NETINFL_r \qquad (45)$$

$$\begin{aligned} GDPVA_r \quad = \quad & \sum\nolimits_f \sum\nolimits_t PF_{f,r} \cdot DF_{f,t,r} \quad + \sum\nolimits_s \sum\nolimits_t ERT_r \cdot \left(tm_{t,s,r} \cdot pwm_{t,s,r} \cdot X_{t,s,r} \right) \\ & + \sum\nolimits_s \sum\nolimits_t te_{t,r,s} \cdot PE_{t,r} \cdot X_{t,r,s} \quad + \sum\nolimits_t ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r} \\ & + \sum\nolimits_t tc_{t,r} \cdot PX_{t,r} \cdot \left(C_{t,r} + GC_{t,r} + ID_{t,r} \right) \end{aligned}$$

(46)

$$PINDEX_r \quad = \quad \frac{GDPVA_r}{GDPR_r} \qquad (47)$$

General Equilibrium and Closure Equations

$$SX_{t,r} \quad = \quad C_{t,r} \quad + \quad GC_{t,r} \quad + \quad ID_{t,r} \quad + \quad \sum\nolimits_k IX_{t,k,r} \qquad (48)$$

$$\sum\nolimits_t DF_{ff0,t,r} \quad = \quad FS_{ff0,r} \cdot FP_{ff0,r} \qquad (49)$$

$$P_{t,r} \cdot Q_{t,r} \quad = \quad PN_{t,r} \cdot NX_{t,r} \quad + \quad PEN_{t,r} \cdot EN_{t,r} \quad + \quad VC_{t,r} \cdot VA_{t,r} \quad + \quad ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r} \tag{50}$$

$$INV_r \quad = \quad deprt_r \cdot FS_{"cap",r} \quad + \quad CPI_r \cdot SAV_r \quad + \quad GSAV_r \quad - \quad ERT_r \cdot NETINFL_r \tag{51}$$

$$INV_r \quad = \quad inv\_s_r \cdot GDPR_r \tag{52}$$

$$GPUR_r \quad = \quad gpur\_s_r \cdot GDPR_r \tag{53}$$

$$GTRANS_r \quad = \quad gtrans\_s_r \cdot GDPR_r \tag{54}$$

$$GREV_r \quad = \quad GPUR_r \quad + \quad GTRANS_r \quad + \quad GSAV_r \tag{55}$$

$$\sum_r NETINFL_r \quad = \quad 0 \tag{56}$$

Table A2: Model Variable Listing

$PWE_{t,s,r}$	World price (seller price FOB)
$PE_{t,r}$	Exported goods price
$PWM_{t,s,r}$	Buyer price (CIF)
$PM_{t,r}$	Aggregate imported goods price
$PX_{t,r}$	Composite goods price
$PD_{t,r}$	Domestic goods price
$P_{t,r}$	Average output price
$PTC_{t,r}$	Sectoral unit cost of production
$PVE_{t,r}$	Value added-energy composite price
$PVC_{t,r}$	Value added composite price
$PEN_{t,r}$	Energy composite price
$PN_{t,r}$	Intermediate good composite price
$PFN_{f,r}$	Factor price (net of tax)
$PF_{f,r}$	Factor price (gross of tax)
$PC_{t,r}$	Consumer purchase price
CPI_{r}	Consumer price index
ERT_{r}	Exchange rate
$VE_{t,r}$	Value added-energy composite good
$VA_{t,r}$	Value added composite
$EN_{t,r}$	Energy composite
$VC_{t,r}$	Sectoral variable production cost
$NX_{t,r}$	Composite intermediate good

$IX_{t,k,r}$	Intermediate demand
$DF_{f,t,r}$	Sectoral factor demand
$C_{t,r}$	Household consumption
$GC_{t,r}$	Government consumption
$ID_{t,r}$	Investment demand
$SUPY_r$	Household consumption above subsistence level
$SX_{t,r}$	Composite good supply
$DX_{t,r}$	Sales of domestic good
$X_{t,s,r}$	Trade flows
$EX_{t,r}$	Exports
$MX_{t,r}$	Sectoral imports by region
$TRQS_r$	International shipping supply by region
PTR	International shipping service price
$TRQD_{t,r}$	International shipping demand by region
TRQ	Total international transport supply
HDI_r	Household disposable income
SAV_r	Household savings
$GREV_r$	Government revenue
$TARIFF_r$	Tariff revenue
$ETAX_r$	Export tax revenue
$PTAX_r$	Output tax revenue (inclusive of intermediate input taxes)
$CTAX_r$	Consumption tax revenue
$FTAX_r$	Factor tax revenue

$HTAX_r$	Household tax revenue
$NETINFL_r$	Net capital inflow by country
$CO2TAXF_{t1,r}$	Carbon tax per fuel
$CO2TAX_r$	Country carbon tax
$CO2TAXR_r$	Country carbon tax revenue
$CO2TOT_r$	Total CO_2 emissions by country
$GDPR_r$	GDP (final demand)
$GDPVA_r$	GDP (value added)
$PINDEX_r$	GDP deflator (*numeraire*)
$Q_{t,r}$	Sectoral output
$FS_{f,r}$	Factor endowment by region
INV_r	Gross investment by region
$GSAV_r$	Government savings
$GPUR_r$	Government purchases
$GTRANS_r$	Net government transfers

Table A3: Model Parameter Listing

$te_{t,r,s}$	Export tax rate
$trs_{t,s,r}$	Transportation cost
$tm_{t,s,r}$	Tariff rate
$\zeta_{t,r}$	Unit cost share parameter
σ^{n}	Unit cost elasticity
$\eta_{t,r}$	Value added-energy composite share parameter
σ^{ve}	Value added-energy composite elasticity
$\delta_{f,t,r}$	Value added composite share parameter
σ^{v}	Value added composite elasticity
$\kappa_{t5,t,r}$	Energy composite share parameter
σ^{en}	Energy composite elasticity
$io_{t6,t,r}$	Input-output coefficient
λ_{r}	Tax rate shift parameter
$tf_{f,r}$	Factor tax rate
$tc_{t,r}$	Consumption tax rate
MT_{r}	Maximum working time
β_{r}^{0}	Leisure share parameter
$\beta_{t,r}$	Sectoral household consumption budget share
$\gamma_{t,r}$	Minimum consumption in LES
$\beta_{t,r}^{CC}$	Sectoral government consumption budget share

$\beta_{t,r}^{ID}$	Sectoral investment budget share
$\alpha_{t,r}$	Absorption share parameter
σ^{m}	Armington elasticity
σ^{t}	Lower level Armington elasticity
$ts_{t,s,r}$	Transportation share parameter
its_{rr}	International transportation share parameter
$deprt_{r}$	Depreciation rate
$ty_{t,r}$	Output tax rate
th_{r}	Household tax rate
$\theta_{t1,r}^{f}$	Carbon intensity by fuel
$\theta_{t1,t,r}$	Carbon emissions factor by fuel and sector
[illegible]	Carbon emissions cap by country (percent of base year emissions)
$pwm_{t,s,r}$	World price of imports
inv_s_{r}	Investment expenditure as a percentage of GDP
$gpur\_s_{r}$	Government purchases as a percentage of GDP
$gtrans\_s_{r}$	Government transfers as a percentage of GDP

Table A4: Model Sets

t, *k*	Sectors
r, s	Countries/regions
rr	All regions except USA
f	Factors
ff0	All factors except natural resources
t1	Fossil fuel sectors
t5	Energy sectors (fossil fuels and electricity)
t6	Non-energy sectors

Figure 1: Decomposition of Change in CO_2 Emissions (1)

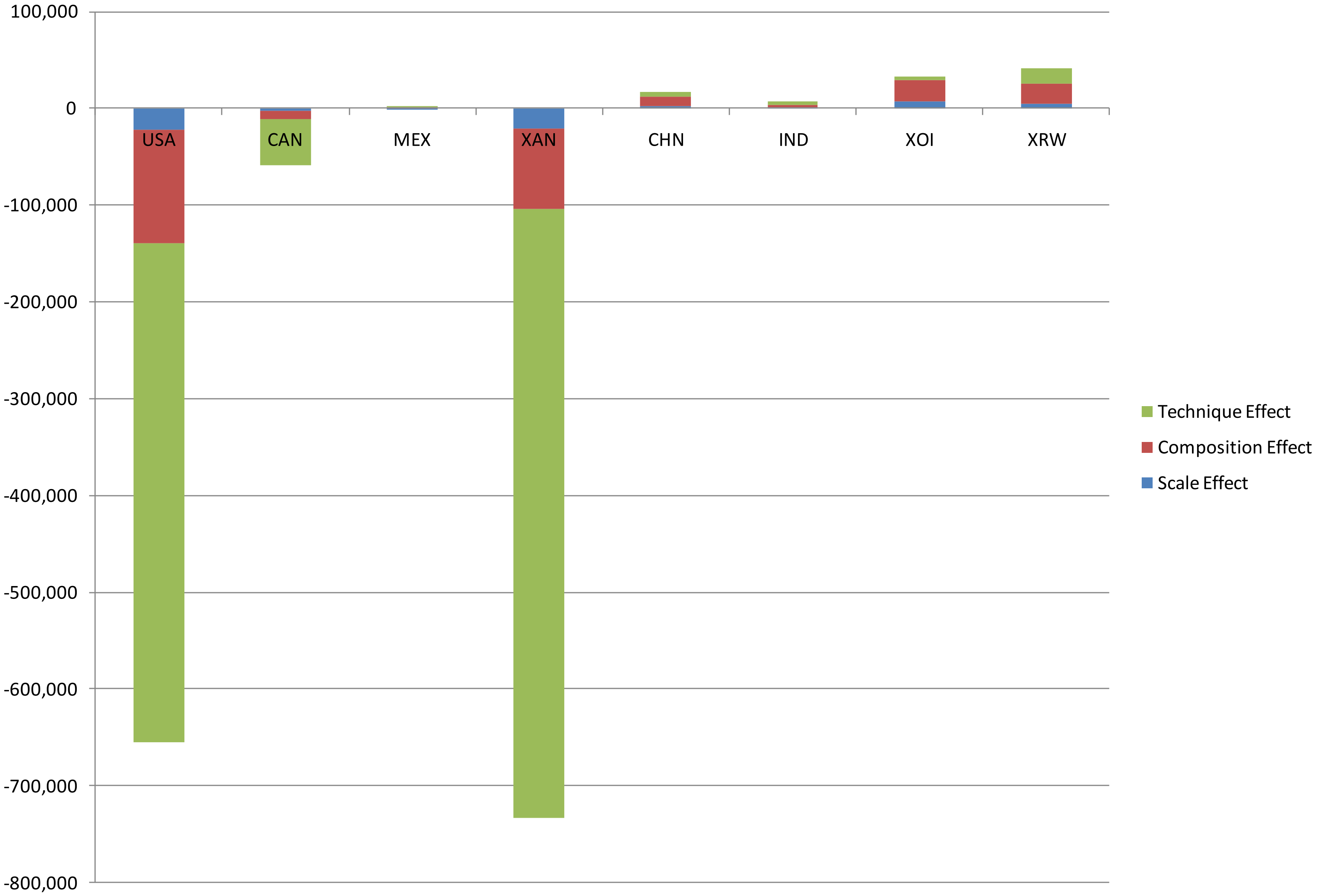

Figure 2: Decomposition of Change in CO_2 Emissions (2)

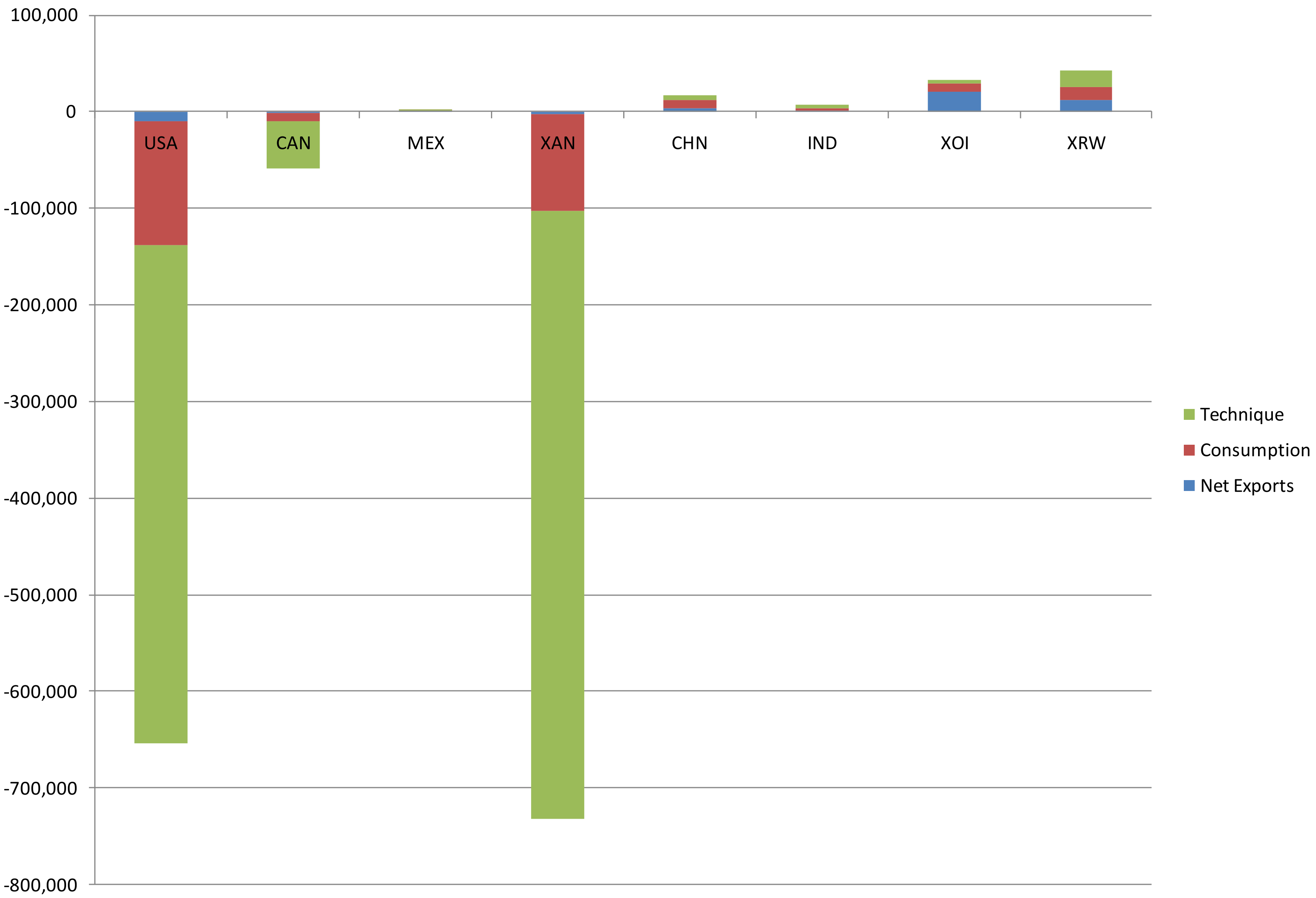

Figure 3: Decomposition of Change in CO_2 Emissions in U.S.

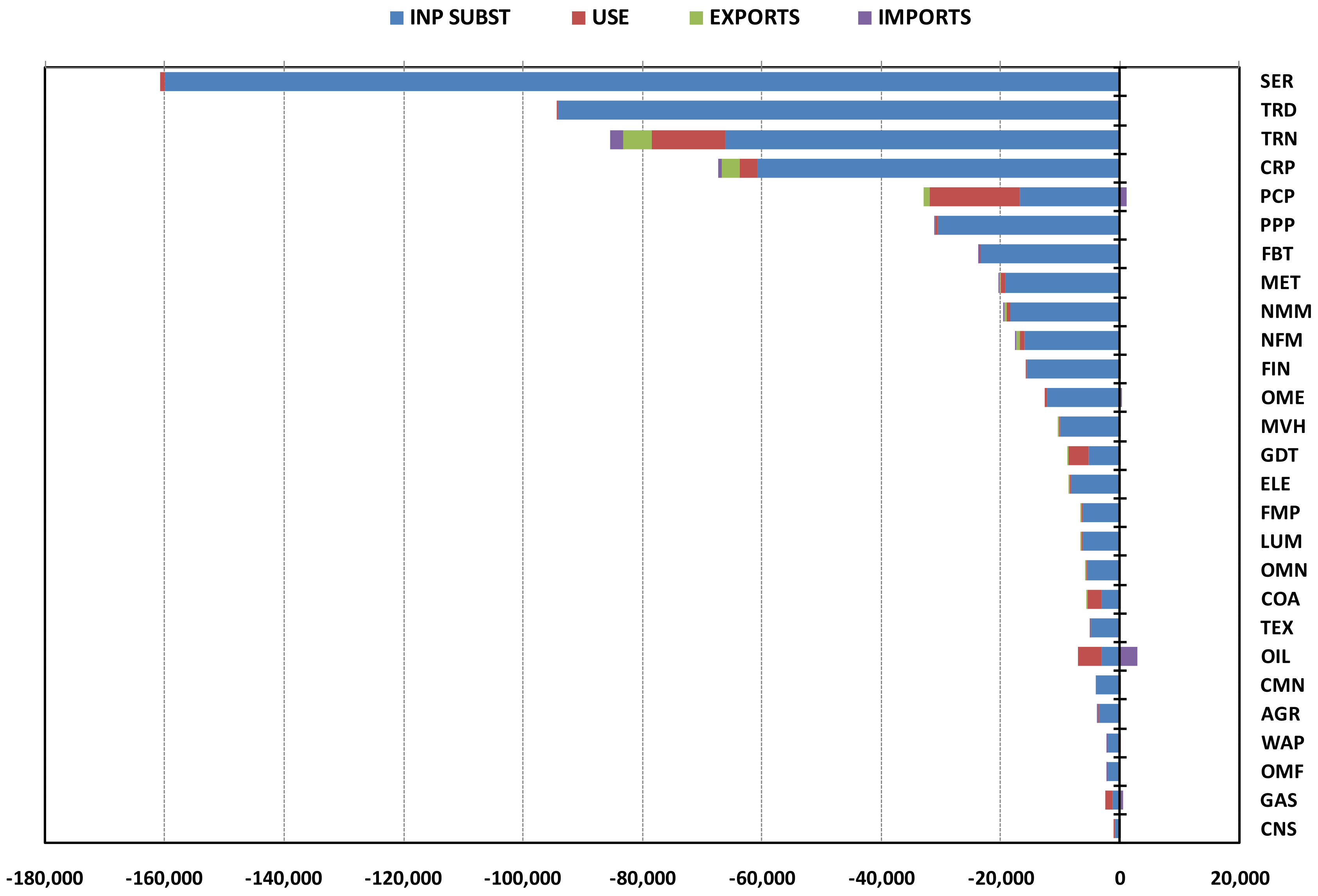

Figure B1: Leakage Rate as a Function of Coal Resource Elasticity