The Welfare Consequences of Taxing Carbon

Dale W. Jorgenson, Richard J. Goettle, Mun S. Ho and Peter J. Wilcoxen*
September 12, 2017

Abstract

For EMF 32, we applied a new version of our Intertemporal General Equilibrium Model (IGEM) based on the North American Industry Classification System (NAICS). We simulated the impacts arising from the Energy Modeling Forum's broad range of carbon taxes under three revenue recycling options – lump sum redistributions, capital tax reductions, and labor tax cuts. We examined their consequences for industry prices and quantities, for the overall economy, and for the welfare of households, individuals, and society, the latter in terms of efficiency and equity.

We find CO_2 emissions abatement to be invariant to the chosen recycling scheme. This means that policy makers need not compromise their environmental objectives when designing carbon tax swap options.

Reducing capital taxes promotes new saving, investment and capital formation and is the most favorable recycling mechanism. In 2010 dollars, the welfare loss per ton abated ranges from $0.19 to $11.21 depending on the path of carbon prices. Reducing labor taxes promotes consumption and work through real-wage incentives and is the next most favorable recycling scheme. Here, the welfare loss per ton abated ranges from $11.09 to $26.39 depending on the carbon tax trajectory. Lump sum redistribution of carbon tax revenues is the least favorable recycling option. It incentivizes neither capital nor labor. Consequently, the damages to the economy and welfare are the greatest among the three schemes. With lump sum recycling, the welfare loss per ton abated ranges from $37.15 to $55.31 as carbon taxation becomes more aggressive.

We find welfare gains are possible under capital and labor tax recycling when emissions accounting is viewed from a supply rather than a demand perspective and carbon pricing is at an economy-wide average. However, these gains occur at the expense of abatement.

We find capital tax recycling to be regressive while labor tax recycling is progressive as is redistribution through lump sums. Moreover, we find that the lump sum mechanism provides the best means for sheltering the poorest from the welfare consequences of carbon taxation. Thus, promoting capital formation is the best use of carbon tax revenues in terms of reducing the magnitudes of welfare losses while the lump sum and labor tax options are the best uses for reducing inequality.

Jorgenson: Dept. of Economics, Harvard University, Goettle: DJA, Ho: SEAS, Harvard University, Wilcoxen: Maxwell School, Syracuse University. This research report is prepared for the U.S. Environmental Protection Agency, Office of Atmospheric Programs.

1. Introduction

For the Energy Modeling Forum's assessment of US policies on carbon taxation and revenue recycling (EMF 32), we apply a new version of our Intertemporal General Equilibrium Model (IGEM). We simulate the impacts on individual, household and societal welfare arising from the broad range of carbon taxes and revenue recycling options posited for the EMF 32 model comparison. We follow the path from the introduction of a carbon tax-and-swap pairing to their effects on industry prices and quantities, and then consider their macroeconomic consequences from both the demand-expenditure and supply-income perspectives. We examine the welfare implications of these pairings in terms of both efficiency and equity. At the household level, these are measured by equivalent variations in lifetime full expenditure (goods, services, and leisure) for demographic groups. At the individual level, these same equivalent variations are examined by quintile. We apply a social welfare function that aggregates over the households and permits the decomposition of welfare change into changes in efficiency and equity. The function is flexible and we consider both egalitarian and utilitarian aversions to inequality.

While our emphasis is on the above, we explore the carbon tax "haircut" that is of concern to policy makers and modelers alike. The haircut refers to the general equilibrium effect of having the actual offsetting reduction in existing taxes be less than expected from a simple, partial equilibrium, calculation of carbon tax receipts. We offer a temporal view of the carbon tax revenues that need to be retained to achieve the EMF 32 fiscal objectives, in line with the increased use of dynamic scoring in policy assessment.

Finally, we examine issues arising from the heterogeneity in prices that underlie transactions in Social Accounting Matrices (SAMs) and the incidence of carbon taxation. For pricing, this is the difference between emissions pricing according to attribution and emissions pricing at an economy-wide average. For incidence, this is a matter of coverage and which buyers bear the burdens of pricing carbon. In the extreme, these relate to the difference between modeling emissions on the demand side and modeling them on the supply side. By measuring the magnitude of this difference, we demonstrate its significance in model outcomes and, equally, in model and policy design.

The new IGEM is based on the North American Industry Classification System (NAICS) and is estimated econometrically over a time series of IO tables covering the years 1960-2010. It is structured around 36 industries and commodities – 1 each of agriculture, construction, and transportation, 6 of energy, 15 of mining and manufacturing and 12 of services. Oil and gas mining now are separated and along with coal, refined petroleum and electric and gas utilities comprise IGEM's energy sectors. The manufacturing and services groups offer a more contemporary view of the U.S. economy; information technology sectors – hardware and software, wholesale and retail trade, finance, business services, education, and health and welfare are among the revised model aggregates.

Table 1.1 presents the eight scenario groups that form the EMF 32 carbon tax trajectories. All carbon tax paths begin in 2020, grow and, at some point, achieve a constant, steady-state level for future years in terms of GDP purchasing power. Five of the eight scenarios have predetermined carbon prices. Four of the five represent all possible combinations of two starting carbon prices – \$25 and \$50 in 2010 dollars – and two growth rates – 1% and 5%. The fifth specified tax path follows that of the Social Cost of Carbon (SCC) under a 3% discount rate. The

SCC trajectory is similar to the \$50 @ 1% path with a 12% lower price in 2020 but a 7% higher price by 2050[1].

[Table 1.1 about here]

For the remaining three EMF 32 scenarios, we solve for the IGEM tax path that achieves a specific environmental policy goal. For the Clean Power Plan (CPP) Match, we impose a carbon tax on the CO_2 emissions from fossil fuel combustion in the electric sector. The tax begins in 2020 and rises at a 5% rate through 2030 after which it remains constant in real terms. The resulting tax achieves an annual rate of emissions in 2030 of 1,551 million metric tons CO_2 (mmtCO_2) from the electric sector. For the 2025 Target scenario, we solve for the tax path that begins in 2020, rises at a 5% rate to a constant level in 2050 while achieving an annual rate of emissions in 2025 of 4,445 mmtCO_2. In this case, we impose the carbon tax on the CO_2 emissions from fossil fuel combustion economy wide. For the 2025 & 2050 Targets scenario, we solve for the initial carbon price *and* growth rate that achieves the same 2025 target of 4,445 mmtCO_2 and also a 2050 target of 1,384 mmtCO_2.

Consistent with the EMF 32 study plan, we simulate IGEM under conditions of debt and deficit neutrality for both government and the rest of the world. Under this condition, if we do not cut existing taxes, carbon tax receipts would fund additional government spending. However, a central purpose of this exercise is to explore the consequences for abatement and the overall economy of alternative revenue redistribution schemes. To this end, we return carbon tax receipts to the private sector through tax swaps while preserving the annual purchases of goods and services by government in the base case path. We employ three recycling mechanisms – lump sum redistribution, capital tax rate reductions, and labor tax rate reductions. For one scenario – \$25 @ 5%, we also recycle using both lump sum transfers and capital tax rate reductions; one case with "equiproportional" changes where the transfer share of income and capital tax rates are scaled equally, and one case where the transfer share and tax rate are adjusted so that social welfare is halfway between the pure lump sum and pure capital tax cases. Aside from small price changes, the combination of deficit neutralities and unchanged real government spending places the adjustment burden of carbon taxes on domestic saving and investment and the international terms of trade.

We organize the remainder of our paper as follows. In Section 2, we provide a brief overview of IGEM's structure and equations with emphasis on household, individual and social welfare. We discuss emissions and their abatement arising in each scenario in Section 3. In Section 4, we describe the interindustry and macroeconomic adjustments to carbon taxes from both demand- and supply-side perspectives. In Section 5, we offer our approach to the dynamic scoring carbon tax policy. In Sections 6 and 7, we examine the welfare implications of carbon taxation, first for households and individuals, Section 6, and, next for society, Section 7. In Section 8, we highlight the differences in model outcomes that follow from demand-side versus supply-side emissions modeling. Finally, in Section 9, we summarize the major findings and conclusions from IGEM's application to the scenarios of EMF 32. We must emphasize that our focus, and that of EMF 32, lies only on the consequences of carbon taxation for the US economy and the welfare of its residents; there is no measurement of or consideration given to the environmental or climate benefits or cost mitigations that arise from emissions abatement.

---

[1] We use the notation "\$50 @ 1%" to mean the carbon tax scenario that starts at \$50 per ton and rising at 1% per year in real terms.

2. The IGEM-N Model and Implementation of EMF32

The Intertemporal General Equilibrium Model (IGEM) of the U.S. economy is described in detail in Jorgenson et al. (2013). This paper uses a substantially revised version of that model and we summarize the key features here that pertain to emission accounting and welfare analysis of the carbon policies in EMF32. We call this version IGEM-N to signify that the industry structure is based on the North American Industry Classification System (NAICS). The detailed equations of the model are given in a separate Appendix (Jorgenson et al. 2017)[2].

2.1 Production

IGEM-N recognizes 36 sectors, of which 6 are energy related, including two for gas mining and gas utilities[3]. There is an Information Technology equipment industry that has very high total factor productivity (TFP) growth that is projected to continue, and 12 service sectors with low projected TFP growth. The production sub-model is represented by a tier structure as in most multi-sector models; however, unlike most systems based on constant-elasticity-of-substitution (CES) functions with 2 aggregated inputs, we use a flexible cost function with up to 4 inputs. At the top tier, output in industry *j* is made from capital, labor, energy, and non-energy intermediates:

$$(2.1) \quad QI_{jt}(KD, LD, E, M; t)$$

The translog cost function we use allows a greater flexibility in substitution between energy and capital, labor and non-energy intermediates, compared to a nested function, e.g., $QI_{jt}(VE[KE(KD,E),LD],M)$.

Secondly, the cost function allows productivity change to be affected by input prices, that is, technical change has an endogenous component. This effect is also referred to as "biased technical change"; a well-known example is the rising hires of highly educated workers even as the relative price of such workers was rising. This allows the model to project a continuing energy-using or energy-saving bias in technical change (a change that uses more, or less, energy over time as energy prices rise, separate from the contemporaneous substitution effect).

There is also an exogenous technical change component that allows us to project TFP growth that differs by industry according to historical rates. This means that relative prices in the future are quite different from base year prices. The estimated parameters are reported in the model documentation update as noted in footnote 2, and the implied substitution elasticities have been reported to the EMF32 team. We note that a base case projection with our estimated parameters will differ from the EMF32 specifications for GDP growth and consumption of the

---

[2] "IGEM, a Model of U.S. Growth and the Environment. Version 20. Appendix A. Equations of the Model" by Jorgenson, Goettle, Ho and Wilcoxen (2017), is available at http://www.igem.insightworks.com/docs/ . Also available are updated Chapters of Jorgenson et al. (2013) that describes the economic history based on this NAICS dataset.

[3] The (2013) version is based on the SIC and only identifies one "oil and gas mining" sector. That model was estimated over 1960-2005 data whereas the current version estimates the production, import, export and investment functions over 1960-2010 input-output data in NAICS.

various fossil fuels. We calibrate the model to these external requirements in a manner described in Jorgenson et al. (2013, Chapter 6).

2.2 Relation between industry quantities and national totals

The accounting of emissions is an accounting of energy inputs into industry and households; and this is often not a transparent exercise in a multi-sector model. We give a short explicit description here to highlight the pitfalls and confusion that might arise in reconciling the observed prices that differ by industry with the typical model assumption of a homogenous good. The main example is the coal mining industry where prices ($ per ton) paid by electric utilities differ substantially from prices paid by other industries; that is, a $100 million worth of coal input in the input-output accounts buys very different number of tons for different industries.

In equation (1), for example, $QI_{coal,t}$ is the quantity index of output of the coal sector, and $PI_{coal,t}$ is the price, i.e. the price of average coal. To simplify the discussion, we ignore imports and the distinction between industries and commodities in this section. The supply equal demand condition in value terms is written as:

$$(2.2)\qquad PI_{it}QI_{it} = \sum_j PB_{ijt}AA_{ijt} + PB_{i,Ct}C_{it} + PB_{i,Gt}G_{it} + PB_{i,Xt}X_{it}$$

where AA_{ijt} is the quantity of *i* bought as intermediate inputs by industry *j*, and C,G,X are household, government and export demand, respectively. PB_{ijt} denotes the buyer's price paid by *j*. Using data on actual prices (or actual quantities), we could write the quantity balance equation as:

$$(2.3)\qquad QI_{it} = \sum_j \xi_{ijt}AA_{ijt} + \xi_{iCt}C_{it} + \ldots$$

where the aggregation coefficients are given by the actual price data in some base year 0:

$$(2.4)\qquad \xi_{ij0} = PB_{ij0} / PI_{i0} .$$

If a model has an equation like (2.3), then the input quantity variable, $AA_{coal,jt}$, would reflect the actual tons of coal used by j. Energy and emission accounts built off $AA_{coal,jt}$ would be consistent with the EIA industry accounts. If a model ignores this observed differences in prices (assuming $PB_{ijt} = PI_{it}$), and write the quantity balance as:

$$(2.5)\qquad QI_{jt}^{mean} = \sum_i AA_{ijt}^{mean} + C_{it}^{mean} + \ldots ,$$

then the $AA_{coal,jt}^{mean}$ variable could differ significantly from actual tons.

We refer to an accounting using QI_{jt}^{mean} as supply-side or top-down accounting, and that using QI_{jt} and AA_{ijt} as demand-side or bottom-up accounting. These two measures of total coal output would coincide only in the base year. In a base case growth path that show big changes in the structure of the economy, i.e. big changes in employment shares by industry, they will diverge. A carbon tax implemented simply as a unit tax on output ($PI_{coal,t} + tx_{coal,t}^{CO2}$) will differ in its effects as a tax implemented as a tax on the buyer's price ($PB_{coal,jt} + tx_{coal,t}^{CO2}$). In the results section, we report the impacts of both supply-side taxes and demand-side taxes.

2.3 Consumption and Household Welfare

The household sub-model drives commodity demand in IGEM-N, determines labor supply and private savings. In this version, we have an aggregate Euler equation that determines aggregate full consumption and savings in each period. In the second stage, we have an aggregate function that determines commodity and leisure demand; a function that is a consistent aggregate over different household demands. This approach allows us to recognize the different consumption choices by different types of households, and to allow income elasticities to be different from 1. The consistent (or, exact) aggregation condition means that the demand for commodity *i* derived from the aggregate function is exactly equal to the sum over the demands for *i* by different households:

$$(2.6) \qquad C_{it}^X = \sum_K C_{iKt}^X$$

The *K* index runs over the demographic types (number of children: 0,1,2,3+; number of adults: 1,2,3+; region: NW, MW, S, W; urban/rural; male/female and white/nonwhite head). There are 384 possible combinations of these characteristics, but only 244 are observed in the Consumer Expenditure Survey.

.

This consistency is delivered by a somewhat complicated utility function at the top tier, *V(ND,K,SV,R)*; where the consumption bundles are nondurables (ND), capital services (K), services (SV), and leisure (R). We begin with the indirect utility function for household *k*, $V_k(p^C, m_k; A_k)$:

$$(2.7) \qquad \ln V_k = \alpha_0 + \alpha^H \ln\frac{p}{m_k} + \tfrac{1}{2}\ln\frac{p}{m_k}' B^H \ln\frac{p}{m_k} + \ln\frac{p}{m_k}' B_A A_k$$

$$p_t^{C}{}' = (PC_{ND}, PC_K, PC_{SV}, PC_R)$$

where m_k is the total full expenditures of *k* and A_k is a (0,1) indicator vector for demographic characteristics.[4] "Full" refers to the sum of goods and leisure. The aggregate demand equation derived by adding over all households, in share form, is:

$$(2.8) \qquad w_t = \frac{1}{D(p_t^C)}\left[\alpha^H + B^H \ln p_t^C - B_M(\xi_t^{dd} + \ln M_t) + B_A \xi_t^L\right]$$

$$w_t' = \left(\frac{PC_{ND}C_{ND}^X}{M}, \frac{PC_K C_K^X}{M}, \frac{PC_{SV}C_{SV}^X}{M}, \frac{PC_R C_R^X}{M}\right);$$

where $M_t = \sum_k m_{kt}$ is the aggregate value of full expenditures (full income minus savings), and the C_i^X's are the consumption quantities. B_M gives the income elasticity and B_A gives the different intercept values for different household types (e.g. households with children have a bigger share for nondurables). ξ_t^L is a distribution term that represents the projected demographic changes in household structure that are paired with the B_A coefficients. ξ_t^{dd} is an

---

[4] The household model equations are given in detail in Jorgenson et al. (2017), Appendix A, equations (A1.12) through (A1.24).

exogenous term that depends on $\sum_k m_{kt} \ln m_{kt}$ and projects the changing share of total *M* spent by households of type *K*. These distribution terms involve the projection of the number of households of each type derived from a population model.

The price elasticity matrix, B^H, is 4x4 matrix that allows a flexible substitution among the 3 commodity bundles and leisure; it is not restricted to a 2-input tier structure or a simple Linear Expenditure System. Below this top tier utility function, there is a nest of similar functions that allocates the 3 bundles to 36 commodities that are identified in IGEM-N. The parameters for the top tier are estimated over Consumer Expenditure Survey data (the CEX covers 4-8000 households per quarter), 1980-2006, the lower tiers use the Personal Consumption Expenditures in the National Accounts, 1960-2010. The estimates are given in Jorgenson et al. (2013, Chapter 3).

To compute household and aggregate welfare we begin with the model solution path for aggregate expenditure and prices: M_t and p_t^C. There are a total of 244 distinct demographic groups[5] and the CEX sample consists of dozens of households in each group per year. For each group we have the actual distribution of household expenditures in 2006. We allocate the simulated aggregate expenditure to the different households using the projected number of households of each type (nf_K) and computing the mean expenditure in type *K* ($M_t = \sum_K nf_{Kt} \bar{m}_{Kt}$). The expenditures by type *K* households are derived by holding them proportional to observed base year values:

$$(2.9) \quad \bar{m}_{Kt} = \mu_{Kt}^0 M_t$$

where μ_{Kt}^0 depends on nf_{Kt} and the base year spending ($\bar{m}_K^{2006}$). With this mean expenditure and prices, we compute the utility for type *K* households for each period (V_{Kt}) using equation (2.7).

Household welfare is a discounted sum of this within-period V_{kt}. We regard households to be infinite-lived dynasties, and the utility of dynasty *d* is:

$$(2.10) \quad V_d = \sum_{t=0}^{\infty} \delta^t \ln V_{dt}$$

Jorgenson et al. (2017) shows how an intertemporal expenditure function, $\Omega_d(\{p_t\},\{\gamma_t\},V_d)$, may be derived from the entire path of prices and interest rates, giving a dollar measure of dynastic utility[6]. We call Ω_d "full wealth," and it equals the present value of the infinite stream of goods consumption and leisure. We emphasize that the demographic coefficients (B_A) result in different values of Ω_d for the same levels of utility for different types of dynasties. This Ω_d function is used to compute the equivalent variation of a policy change that changes utility from V_d^0 in the base case to V_d^1 in the policy case:

$$(2.11) \quad \Delta W_d = EV_d = \Omega_d(\{p_t^0\},\{\gamma_t^0\},V_d^1) - \Omega_d(\{p_t^0\},\{\gamma_t^0\},V_d^0)$$

---

[55] The demographic characteristics we identify are: number of children (0,1,2,3+), number of adults (1,2,3+), region (2.4), urban/rural, gender of head (2), race of head (2). Some combinations have zero households in the sample and so we have only 244 groups.

[6] Jorgenson et al. (2017, Chapter 3), equation 3.67.

2.4 Social Welfare; Aggregate

To discuss the policy impact on social welfare, in addition to calculating the impact on household welfare, we specify a social welfare function that takes into account both the mean and the distribution of household welfare:

$$(2.12)\quad W = \bar{V} - \eta\left[\sum_{d=1}^{D} a_d \left|V_d - \bar{V}\right|^{-\mu}\right]^{-1/\mu}$$

$\bar{V} = \sum_{d=1}^{D} a_d V_d$ is a weighted sum of dynastic welfare where the weights are related to the number of "household equivalent members." Parameter μ is a measure of social aversion to inequality, where $\mu = -1$ gives the greatest weight to equity ($W^{Egalitarian}$), and $\mu = -\infty$ gives an utilitarian function where $W^{Utilitarian} = \bar{V}$.

Maximum social welfare ($W_{\max}$) is attained by reallocating incomes to equalize welfare across dynasties (details in Jorgenson et al. 2017, Section 3.8):

$$(2.13)\quad W_{\max} = \bar{V} = f(\frac{\Omega}{N^{eq}})$$

This maximum, or *efficient*, social welfare is a function of national full wealth (Ω) divided by the number of "household equivalent members," N^{eq}.

We derive a monetary measure of social welfare using a social expenditure function $\Omega(\{p_t\},\{\gamma_t\},W)$ that depends on the entire time path of prices and interest rates[7]. The national equivalent variation of a policy change (ΔW) is given by calculating the social full wealth, Ω, for the base case social welfare (W^0), and for policy case welfare (W^1) at base case prices:

$$(2.14)\quad \Delta W = \Omega(\{p_t^0\},\{\gamma_t^0\},W^1) - \Omega(\{p_t^0\},\{\gamma_t^0\},W^0)$$

We decompose this equivalent variation to a change in efficiency and a change in equity. The change in efficiency is the change in Ω measured at the perfectly egalitarian distribution of wealth:

$$(2.15)\quad \Delta E = \Omega(\{p_t^0\},\{\gamma_t^0\},W_{\max}^1) - \Omega(\{p_t^0\},\{\gamma_t^0\},W_{\max}^0)$$

The change in the money measure of equity (ΔEQ) is then given by the residual from (2.14) and (2.15):

$$(2.16)\quad \Delta W = \Delta E + \Delta EQ$$

---

[7] Jorgenson et al. (2017, Chapter 3), equation 3.77.

When we report the policy impacts, we give the equivalent variation as a percent of full wealth, $\%EV = \dfrac{\Delta W}{\Omega(\{p_t^0\},\{\gamma_t^0\},W)}$.

2.5 Implementing carbon prices and revenue recycling

The policies in EMF32 call for recycling carbon tax revenues using (1) lump sum rebates to households, (2) cutting capital tax rates, or (3) cutting labor tax rates. To implement a lump sum rebate that is proportional to household expenditures we rewrite dynasty *d*'s expenditure (equation 2.9) by adding the total rebate to national full expenditures (M_t):

$$\text{(2.17a)} \qquad \bar{M}_{dt}^{propor} = \mu_{dt}^0 (M_t + TLUMP)$$

If the rebate is given equally per capita, the dynasty expenditures is:

$$\text{(2.17b)} \qquad \bar{M}_{dt}^{percap} = \mu_{dt}^0 M_t + \frac{nm_d}{n_t^{pop}} TLUMP$$

where nm_d is the mean number of members in household of type *d* and n_t^{pop} is the total population (Jorgenson et al. 2017, equation 3.93-95). If revenue is recycled by cutting capital or labor taxes, this will be reflected in different disposable incomes, and hence different values of aggregate full expenditures, M_t.

2.6 Social welfare; distribution

We portray the distributional effects of policy by first ranking the 244 household types in order of the full expenditures per person. Equations (2.9), (2.17a) and (2.17b) give the average M_{dt} for each type, depending on the recycling policy. Equation (2.6) gives the lifetime utility, V_d, and $\Omega_d(\{p_t\},\{\gamma_t\},V_d)$ gives the full wealth of dynasty *d* (the money measure of V_d, equation 2.11). Our demographic groups are cross classified by the number of adults and number of children and this gives us the number of household members, nm_d. We can thus calculate the full wealth per capita for the no-policy base case simply as: $\Omega_d^{pc} = \Omega_d / nm_d$.

These full wealth per capita ranges from \$850,000 in 2010 dollars for a 1-adult, 3+ children, nonwhite female headed, rural South household to \$10.3 million for a 2-adult, no children, white female headed, rural Northeast household, for a base case starting in 2015. Let the ordered list of increasing per capita full wealth be denoted by $\Omega_{o(d)}^{pc} \quad o(d) = 1,2,...244$.

The total full wealth of the ordered group *o(d)* is the mean wealth multiplied by the number of households in that group, $\Omega_{o(d)}^{tot} = \Omega_{o(d)} * nf_{o(d)}$. Group *d*'s share of total national full wealth (Ω^{sum}) is given by:

$$\text{(2.18)} \quad \omega_{o(d)}^{tot} = \Omega_{o(d)}^{tot} / \Omega^{sum}$$

The cumulative sum of these group shares, over the o(d) ordering, gives the Lorenz curve (in terms of lifetime full wealth, not the more familiar Lorenz curve for annual income). We can then compute the Gini coefficient from this Lorenz curve, for the base case and policy cases.

To give an alternative picture of the distributional impact, we also divide the population into quintiles according to the population in each ordered group, $n_{o(d)}^{pop}$. In the base case, the lowest quintile consists of 106 groups with the lowest $\Omega_{o(d)}^{pc}$, while the highest quintile consists of the 15 groups with the highest per capita full wealth. (There is 20% of the population in each quintile, but since the number of households in each group varies widely, there is a different number of groups in each quintile.) The lowest quintile has only 10.5% of national full wealth, while the highest has 29.7%[8]. The equivalent variation for a policy for type *d* dynasties is given by (2.11); we cumulate the EV's over all groups in each quintile. This allows us to show how some policies could have a positive EV for the lowest quintile while having a negative total EV for the country.

We also define two measures of inequality in terms of the social expenditure function. An absolute index of equality may be defined as the difference between actual welfare and efficient welfare:

$$(2.19)\quad AEQ(\{p_t^0\},\{\gamma_t^0\},W,W_{\max}) = [\Omega(\{p_t^0\},\{\gamma_t^0\},W)] - \Omega(\{p_t^0\},\{\gamma_t^0\},W_{\max})] < 0$$

A relative measure of equality is:

$$(2.20)\quad REQ(\{p_t^0\},\{\gamma_t^0\},W,W_{\max}) = \frac{\Omega(\{p_t^0\},\{\gamma_t^0\},W)}{\Omega(\{p_t^0\},\{\gamma_t^0\},W_{\max})} < 1$$

The degree of progressivity of a policy change is given by two corresponding progressivity measures evaluating the inequality indices at base case and policy case welfare levels, both at base case prices:

$$(2.21)\quad AP = AEQ(\{p_t^0\},\{\gamma_t^0\},W^1,W_{\max}^1) - AEQ(\{p_t^0\},\{\gamma_t^0\},W^0,W_{\max}^0)$$

$$(2.22)\quad RP = REQ(\{p_t^0\},\{\gamma_t^0\},W^1,W_{\max}^1) - REQ(\{p_t^0\},\{\gamma_t^0\},W^0,W_{\max}^0)$$

3. Emissions Impacts

We begin our discussion of the simulated impacts by describing the carbon tax rates and CO_2 emission targets. The direct taxation of CO_2 and equivalent greenhouse gas (GHG) emissions is an efficient market-based means for securing their reductions. Though not yet considered by the U.S., it is most likely easier to implement and less costly to administer. Table 3.1 shows the cumulative CO_2 emissions and their abatement from fossil fuel combustion in gigatonnes ($GtCO_2$) for the US economy over the period from 2015 through 2050. The extremes are easily identified. The \$25 @ 1% tax path secures emissions reductions in the range of 13 to 14% from base case levels. The high-tax trajectories – \$50 @ 5% and 2025 & 2050 Targets – achieve abatements in the range of 31 to 34% from base case levels. In between, lie the outcomes for the \$25 @ 5%, the \$50 @ 1%, and the SCC tax paths. Cumulative emissions reductions in

---

[8] Note that this method does not fully rank all the 1000s of households in the CEX sample by per capita wealth; we are using only the averages of the 244 types of households to rank these 244 groups. We are using, however, the detailed consumption information for the 244 types, not just the consumption information by quintile.

these scenarios are in the range of 40 to 44 $GtCO_2$ or 21 to 23% from base case levels. The 2025 Target scenario tracks the path of $25 @ 5% but with initial and steady-state carbon prices that are almost 24% lower. Abatement here lies about halfway between that determined for the two $25 tax paths. Finally, by comparison, the CPP Match is quite modest in its goals and accomplishments. Limited both in time and in coverage, the CPP Match achieves cumulative economy-wide abatement of 10.5 $GtCO_2$, of which 10.1 $GtCO_2$ comes from within the electric sector.

Table 3.1 about here

Measuring cumulative emissions alone masks important issues of policy timing and duration. From Table 3.1, it appears that the $25 @ 5% tax path is less effective than either the $50 @ 1% or SCC cases in its abatement potential. Also, despite extremely high carbon prices toward mid-century, it is surprising that the 2025 & 2050 Targets tax path achieves so little more in emissions reductions than does the $50 @ 5% trajectory. In both apparent anomalies, the starting carbon prices are lower, rise at faster rates, and reach substantially higher steady state levels by 2050 than do their comparative scenarios. While the period of interest ends in 2050, the carbon tax remains at its 2050 level in real terms forever. Since IGEM policy simulations span the years from 2015 through 2130 – with all variables in steady state by 2080 at the latest – there is significant abatement occurring after 2050. The two 1% growth scenarios secure post-2050 abatement that is more than two times greater than the figures reported for them in Table 3.1. For the two 5% growth scenarios, post-2050 abatement is more than three times greater than the reported abatement from 2015 to 2050. Thus, in the longer run, the $25 @ 5% tax path achieves emissions reductions that exceed those from both the $50 @ 1% and SCC tax regimes. Similarly, the post-2050 abatement under the $1,000 price of the 2025 & 2050 Targets path is more than five times greater than that achieved pre-2050 and, so, has a much greater abatement potential than does the $50 @ 5% case. In observing IGEM, abatement is obtained more easily under high carbon prices in the earlier years than in the later years but, nevertheless, abatement occurs in all years under all prices; the timing and magnitude of abatement depends on the actual tax path.

The issue of international leakage is a matter of importance in assessing carbon tax policy, especially if the US is assumed to act unilaterally. Unfortunately, a single-country model like IGEM with no endogenous world prices has only a limited ability to describe the trade impacts. With the assumed exogenous current account deficits and foreign debt fixed at base case levels, the terms of trade adjusts as export supplies and import demands respond to the effects of carbon taxation. While we can compute the change in carbon embodied in the U.S. trade flows, we cannot account for changes in emissions in the rest-of-the-world. Under all tax paths and recycling schemes, the relatively small exports of coal, oil and gas decline as well as those of electricity. The imports of coal, oil and gas also decline under all pairings since they are also subject to the carbon price. The small imports of electricity rise in these cases since they are not subject to a carbon price; however, we do not know the generation mix supporting these electricity imports.

As for non-energy trade patterns, the revenue recycling scheme matters. Under lump sum redistribution, all non-energy exports decline except those of educational services which rise slightly. All non-energy imports decline without exception. Non-energy imports also decline under the capital and labor tax swaps with the exceptions of agriculture and food imports under labor tax recycling. The non-energy export story is more varied. Under capital tax recycling, export increases occur in fabricated metals, IT, electrical and transportation equipment, miscellaneous manufacturing, printing, wholesale trade and all of the service commodities with the exceptions accommodations and other government; other non-energy exports decline. With the labor tax option, export increases occur in all commodities except those from the energy-intensive sectors like mining, non-metals, wood and paper, primary metals, machinery, motor vehicles, chemicals and transportation. As with energy, the impacts of these altered trade patterns on global emissions are not determinable in IGEM.

While international carbon leakage is of potential importance in the unilateral design of climate change policy, there is a domestic concern that receives little attention. In IGEM over the period 2010-2050, the CO_2 equivalent emissions from fossil fuel combustion account for only 93% of total CO_2 emissions and only 74% of all GHG emissions. By only taxing the emissions from fossil fuel combustion, there is the possibility of offsetting increases in CO_2 and other GHG emissions unrelated to combustion. Fortunately, this does not occur in IGEM since many of the sources of these other emissions are also major energy users – cement, chemicals, metals, mining. Under all carbon tax and recycling pairings, there occur additional net reductions in both non-combustion CO_2 and GHG emissions. For example, in 2050 under the \$25 @ 5% tax path, there is an additional net reduction of 46.8 mmtCO_2 in non-combustion CO_2 emissions with lump sum redistribution, 39.6 mmtCO_2 with capital tax recycling and 36.1 mmtCO_2 following the labor tax swap. Beyond *total* CO_2 emissions, there is an additional net reduction in GHG emissions of 107.3 mmtCO_2 equivalent (mmtCO_2-e) under lump sum, 90.3 mmtCO_2-e with offsetting capital taxes and 73.4 mmtCO_2-e with lower labor taxes. Under the \$50 @ 5% regime in 2050, the corresponding additional net reductions in non-combustion CO_2 emissions are 76.6, 66.1 and 61.9 mmtCO_2, respectively, and, in GHG emissions, they are 170.0, 144.6 and 119.3 mmtCO_2-e, respectively. Clearly, there is a positive domestic spillover in emissions abatement from the more limited taxation of carbon.

4. Economic Impacts

We next examine the economic impacts of carbon taxes by considering the average adjustments of economic activity over the period 2015-2050.The driving force behind these changes is that prices rise for almost all commodity groups relative to the leisure price numeraire, so that market participants must adjust to higher prices. However, these adjustments differ substantially among different methods for utilizing the tax revenues, reflecting differences in the mechanisms for responding to changes in relative prices.

We present the impacts of alternative carbon policies on prices relative to the labor price numeraire in Tables 4.1 and 4.2. Table 4.1 shows the effects of five of the EMF 32 tax regimes on commodity supply prices under lump-sum redistributions of tax revenues. Table 4.2 shows these outcomes for the \$25 @ 5% tax trajectory for the three recycling scenarios. The price impacts of the other tax trajectories have the same pattern of changes among commodities and differ only in their scale.

4.1 Lump-sum recycling

Energy prices – coal, oil, gas, and electricity – are strongly affected by carbon taxes with the greatest impact on coal prices. This is not surprising in that 74% of greenhouse gas emissions over 2015-2050 are fossil-fuel-related – the use of coal (20%), refined petroleum (31%), and gas (23%); fossil fuels in electricity production alone account for 26%. Coal, with the highest carbon content among the fossil fuels, and gas use in the generation of electricity primarily account for the shock to electricity prices.

We assume that the stock of capital (which includes land and resources) is fixed in the oil and gas mining sectors. This leads to upward sloping oil and gas supply curves. With the reduced demand for crude from petroleum refining due to the carbon tax, the output of this sector falls, lowering the cost of capital and thus lowering prices for domestic crude oil extraction. In gas mining, this demand-supply effect on prices is more than offset by the incidence of carbon taxes on the direct purchases of gas mining output by industry and electric utilities.

All non-energy prices increase under lump-sum recycling. The heavy users of fossil fuel energy and electricity are affected most – agriculture, non-energy mining, the non-metals and metals commodities, machinery, motor vehicles, food, textiles and apparel, chemicals, and transportation. Other sectors and particularly the services commodities are much less affected.

[Tables 4.1 and 4.2 about here]

We next consider the impacts of price changes on economic performance. Table 4.3 shows the impacts on final demand (GDP) and its components, while Table 4.4 presents the outcomes for the capital stock, labor demand and supply, leisure demand and full consumption. These tables summarize all five tax scenarios and all three recycling options; we first discuss lump-sum redistributions, then discuss the capital and labor recycling options.

Among the combinations of carbon-tax levels and fiscal reforms, lump-sum redistributions result in the largest negative impact on both the demand and supply sides of the US economy. Losses in GDP from base-case levels, averaged over 2015-2050, range from just under 0.7% to around 2.5% as carbon-tax rates increase. Losses in consumer spending averages are smaller but in line with the GDP amounts while investment and the trade components experience more significant reductions.

The declines in investment adversely affect capital formation, so that the capital stock averages anywhere from 0.7 to 1.9% lower, depending on the tax trajectory. The reduction in labor use average from 0.5 to 1.7% as carbon tax regimes intensify. An important benefit in these outcomes is the increases in leisure that that accompany this reduction of labor input. Gains range from 0.2 to 0.7%, depending on the tax path, and partially compensate households in terms of full consumption for losses in personal consumption expenditures on goods and services.

[Tables 4.3 and 4.4 about here]

The economic impacts of carbon taxes on the US economy are dominated by the decisions of households. Household decisions begin with the intertemporal allocation of full wealth yielding annual levels of full consumption on goods, services, and leisure. Anticipating price increases from rising carbon taxes, households shift full consumption from the future towards the present. This reduces saving and lowers the rate of capital formation.

Households next choose the allocation of full consumption between goods, services, and leisure. Since carbon taxes make consumer goods and services more expensive relative to leisure, households substitute leisure for goods and services. Although nearer-term full consumption rises, consumption of goods and services declines because lower labor input leads to lower current GDP and real incomes. Increased leisure improves household welfare while reducing personal consumption expenditures reduces it. We evaluate carbon-tax policies in terms of their impacts on the welfare of individuals and households and, ultimately, on social welfare and not in terms of production and spending.

The third set of decisions by households is to allocate the reduced level of household spending among thirty-six commodities including capital services. Personal consumption expenditures are redirected from goods and services with large price increases toward those with smaller price increases. Since household spending is a large fraction of final demand, the decisions of households influence the structure of real GDP and the domestic production activity that supports it.

The production side of the economy is affected adversely by the fall in labor and capital supply due to the carbon taxes. All industries eventually experience declines in output. Industries subject to the carbon tax are especially hard hit. The changes in industry output for the lump-sum case, averaged over 2015-2050, are given for selected tax paths in Table 4.5, and for the three recycling schemes in $25 @ 5% case in Table 4.6. Obviously, the energy sectors are affected most following the imposition of a carbon tax on fossil fuel combustion. Next most affected are the heavy users of fossil fuel energy and electricity – non-energy mining, water treatment, construction, wood and paper, the non-metals and metals commodities, machinery, motor vehicles, textiles and apparel, chemicals, and transportation. Other manufacturing and the services industries are less directly affected by price effects but more so by reduced incomes.

Negative industry output effects result not only from higher prices and declining demands throughout the economy, but also from reductions in the availability of capital and labor inputs. Facing reduced demands for output and more limited factor supplies, producers are forced to raise prices to cover their increase in costs. Producers do their best to insulate their prices from the impacts of more expensive energy inputs. Substitutions from more costly energy toward relatively cheaper materials, labor, and capital inputs help to mitigate the adverse effects.

[Tables 4.5 and 4.6 about here]

The reduction in labor income from the households' reduced labor supply combines with lower capital income from businesses to yield a reduction in the nominal GDP. Personal consumption declines even with the lump-sum redistribution of tax revenues. Private saving also declines. The reduction in saving is accompanied by a corresponding reduction in private investment. With higher prices for investment goods, the available investment funding buys fewer capital goods and leads to a lower capital stock and diminished availability of capital inputs in later years. Reduced capital and labor inputs limit the economy's domestic supply and output potential.

IGEM's saving-investment balance captures the net flow of funds available for investment. Domestic saving must satisfy two important claims before flowing through to investment. The first claim on saving is the combined deficits of governments. The second claim arises from the nation's interactions with the rest of the world. A surplus in the current account balance is, in part, the excess of the value of exports over the value of imports and finances net foreign investment. The funds available for private investment are equal to those remaining from private saving after financing government deficits and net foreign investment. The current account deficits that are projected for the US in the near term imply that domestic saving is augmented by foreign saving in financing US investment.

To capture the impacts of declines in saving we eliminate the direct effects of governments on investment spending. Our scenarios for recycling of government revenues through lump-sum redistributions, as well as recycling through reductions of capital and labor-tax rates, assume no change in the deficits of the government sectors or the levels of real government purchases. Under this assumption the time path of public debt is unaffected by the choice of methods for revenue recycling. However, there is some minor crowding-out of private investment as the relative prices of goods and services to governments change.

All scenarios for recycling carbon-tax revenues hold constant the current account balance and net foreign indebtedness. The current account balance is maintained by the endogenous adjustment of the terms of trade, i.e., the real exchange rate. The prices of US-made goods rise relative to world prices under the effects of the carbon tax. Since we estimate the supplies of exports to be price-elastic, export volumes fall more than export prices rise and the value of exports declines.

The change in imports is more complicated in that we have both income and price effects. Lower real household income reduces lifetime consumption, although consumption in different phases of the transition may rise temporarily, as discussed above. The lower lifetime consumption and lower investment means lower aggregate demand for imported goods and services. Domestic goods not directly subject to the carbon tax still have prices rise relative to world prices, inducing a substitution toward imported varieties that partially offsets the demand effects. Fossil fuel use is subject to the carbon tax and so their imports are indirectly taxed and demand falls.

The opposing income and price effects result in a reduction in aggregate import demand that is smaller than but aligned with the reduction in exports. To maintain the current account balance at base-case levels, market equilibrium requires a long-run depreciation of the exchange rate. With consumption pulled forward in the short term, there is a positive impact on import demand. This requires a short-term appreciation of the exchange rate to maintain the current account balance.

4.2 Cutting taxes on capital and labor

We now turn to revenue recycling through reductions in tax rates, beginning with those on capital. We again hold real government purchases, deficits, and debt at base-case levels. As before, carbon-tax policy raises prices to producers and consumers. Under the \$25 @ 5% carbon-tax trajectory, capital-tax rates average 10.5% lower than in the base case over the period 2015-50. In the \$50 @ 5% trajectory the corresponding reductions average 19.1%.

Recycling carbon-tax revenues through lower tax rates on capital reduces the rental price of capital services and raises the returns on saving and investment and, hence, capital income. Referring to Tables 4.3 and 4.4, this policy favors capital formation over the consumption of goods and services while the higher relative price of labor input leads to lower labor demand and more leisure. This labor-leisure tradeoff occurs at all but the 2025 & 2050 Target path wherein the carbon price gets so high that both incentivized capital and labor substitute for energy and materials in support of production and spending. Overall, the increased availability of capital – averaging from 0.5 to 2.9% as carbon-tax paths rise – helps insulate the US economy from higher prices.

GDP change (averaged over 2015-2050) is positive in the capital tax cut cases unlike the other recycling scenarios. There also is a noticeable partition between the 1% and 5% growth scenarios; GDP increases more with the higher carbon tax growth path.

We also note a change in the trade patterns under capital tax recycling. In comparison to lump sum redistribution, export and import reductions are smaller and they reverse with import reductions proportionally larger than export reductions. With current account neutrality, there is little variation in nominal and real net exports across recycling schemes *within a given carbon tax scenario*. However, there is variation in the components of net exports. Export supplies depend on US competitiveness in world markets as determined by exchange-rate-adjusted domestic prices versus world prices. Import substitutions depend on world competitiveness in US markets *and* the overall commodity demands that imports partially fulfill. As domestic prices, commodity demands and the terms of trade vary from one recycling scheme to another, so too do the levels of exports and imports even though their difference is relatively unaffected.

Compositionally, under the capital tax swap, we find in Table 4.6 a pattern of changes in industrial outputs that reflects both improved economic performance and the investment-driven-consumption-saving nature of that performance. Energy aside, capital tax recycling leads to increases in all things related to investment and capital accumulation. On average, the outputs of non-energy mining, construction, finished metals, the equipment sectors, printing, trade, telecom, and software increase while those related to consumption – agriculture, food, apparel, health care and accommodations – decline.

We next consider the substitution of carbon taxes for labor taxes. The taxes levied on fossil fuel combustion emissions still raise prices to producers and consumers. The increases in carbon-tax revenues are returned to households through reductions in the average and marginal tax rates on labor income. For the $25 @ 5% carbon-tax trajectory, these rate reductions average 7.7% from 2015 through 2050. The $50 @ 5% tax trajectory permits corresponding reductions averaging 13.0%. For broadly similar carbon-tax revenues, the differences in tax bases and tax rates imply that proportional capital-tax reductions must be significantly larger than labor-tax reductions to achieve deficit neutrality.

The labor-tax rate reductions raise the opportunity cost of consuming leisure. As shown in Tables 4.3 and 4.4, households substitute toward consumption and away from leisure. With the numeraire as the leisure price, the changes in the labor-tax rate imply a lower labor input price to employers. Labor demand increases at a reduced pre-tax wage. Producers absorb this additional labor, restructuring inputs toward labor and away from emissions-generating activities and capital. Unit production costs and commodity prices in terms of the numeraire fall relative to the base case *and* the other recycling options. Falling commodity prices against the numeraire yield the rising real wage that incentivizes the demand-matching increase in labor supply.

Labor-tax rate reductions favor consumption over saving and investment. Income rises from greater labor supply, but this is more than offset by a decline in capital income due to a lower capital stock. Given the intertemporal preferences we have estimated and the time profile of real wages, the reduction in lifetime full income is optimized by having higher full consumption in the near term before the carbon tax is imposed and lower full consumption in the longer term. Higher full consumption in the near term combined with higher labor supply means higher goods consumption and reduced saving. Reduced saving leads to reductions in investment and a lower rate of capital formation even with lower prices for investment goods.

Again, there is a noticeable partition between the 1% and 5% growth scenarios. The increases in consumption are larger and the decreases in investment are smaller in the 1% cases than they are in the 5% cases. Moreover, GDP increases under the 1% growth rates but declines under the 5% rates. In the 2025 & 2050 Target case, the eventual tax burden is so high that the effects of reduced saving, investment, and capital accumulation more than offset any benefits from increased labor supply and income and, thus, even consumption declines. The above results clearly suggest that the economy is more capital-sensitive than it is labor-sensitive to carbon tax policy.

The favorable price effects from labor-tax recycling at the commodity level, relative to the leisure price numeraire, are shown in table 4.2. Under this scheme, we see price decreases for all non-energy commodities except transportation which, of course, is fossil-fuel intensive. No other recycling option delivers this effect.

Tables 4.3 and 4.4 show that labor-tax recycling promotes consumption over investment and labor over leisure. Over the four rising carbon tax trajectories, average increases in consumption range from 0.3% to 0.5% with average increases in labor supply in the 0.6 to 1.2% range. The consumption-leisure effects are partially offsetting. With leisure dominating commodities full consumption declines in line with that observed under lump sum redistribution. Here, it is simply the case that the patterns of consumption and leisure are reversed – consumption increases and leisure decreases under labor tax recycling while consumption decreases and leisure increases in the lump sum case.

Under the labor tax option, the declines in investment are quite modest in comparison to lump-sum recycling and yield smaller declines in the capital stock. The effects on the components of trade also are smaller than under lump sum. In percentage terms, export reductions still exceed import reductions and do not reverse as they do under the capital tax option.

Finally, Table 4.6 shows the consumption bias that structurally occurs under labor tax recycling. Now, the industries that benefit from the carbon tax pairing are agriculture, food, apparel, printing, retail trade, finance, education, health care, and accommodations. The capital goods industries are less affected than under the lump sum treatment because investment and the overall economy are less affected but there is still a noticeable redirection away from them.

5. Carbon Taxation and Dynamic Scoring

Federal policy now is examined through the lens of dynamic scoring. Such analysis considers the broad temporal consequences of potential enactment with emphasis on the policy's effects on tax revenue streams, programmatic spending, annual deficits and U.S. indebtedness. By intent and design, we simulate IGEM under the assumptions of deficit and debt neutrality with tax swaps that maintain the annual, real purchases of goods and services by Federal, state and local governments at their base case levels. Accordingly, the scoring metrics for carbon taxation under these assumptions are the annual percentage of carbon tax revenues that are redistributed through reduced taxation elsewhere and its complement, the percentage required to hold government purchases unchanged. The latter is the so-called policy's "haircut." Formally, these are determined as follows.

Annual carbon tax revenues, *CTR*, cover changes between a policy case (denoted with a *P* superscript), and the reference or base case (superscript *R*); changes in the deficit of governments (*DEF*), their expenditures (*EXP*), and their tax revenues from traditional, non-carbon sources (*REV*). Algebraically, (5.1) $CTR = (DEF^R - DEF^P) + (EXP^P - EXP^R) - (REV^P - REV^R)$.

Under deficit neutrality, $(DEF^R\text{-}DEF^P)$ is zero. If, in any simulation involving tax swaps, it is not, then it becomes part of the haircut. However, *DEF* is not part of the haircut if the goal is to use carbon tax revenues to reduce government deficits and debt.

The change in government expenditures, $(EXP^P\text{-}EXP^R)$, covers price changes in government purchases of goods and services, the aggregate of which is constant in real terms under tax recycling. It also covers any endogenous changes in non-final demand outlays (e.g., interest payments on government debt, transfers). No matter the cause or amount, it is part of the haircut in simulations involving tax swaps. However, *EXP* is not part of the haircut if the goal is to use carbon tax revenues to increase government spending.

In IGEM, traditional tax revenues, *REV*, arise from a variety of sources, each involving a tax rate, *trate*, applied to a tax base, *TBASE*. The components of $(REV^P\text{-}REV^R)$ thus take the general form

(5.2) $(trate^P \times TBASE^P - trate^R \times TBASE^R)$.

This change in *REV* can be decomposed[9] as

(5.3) $(trate^P - trate^R) \times TBASE^P + trate^R \times (TBASE^P - TBASE^R)$.

When component tax rates remain unchanged (i.e., revenues are not recycled), $(trate^P - trate^R)$ is zero and there are only general equilibrium effects arising from changes in the tax base, $(TBASE^P - TBASE^R)$. These, like any change in *DEF* and *EXP*, are part of the haircut.

When component tax rates change (i.e., carbon revenues are recycled), $(trate^P - trate^R)$ is negative. There now are recycling effects in addition to general equilibrium tax consequences. Since the goal of recycling is to return as much of the carbon tax receipts as possible, the percentage recycled is given as:

(5.4) $\%rec = (trate^P - trate^R) \times TBASE^P / CTR$

The haircut rate may thus be defined as:

(5.5) $\%h = 1 - (trate^P - trate^R) \times TBASE^P / CTR$.

Table 5.1 shows the percentages of carbon tax revenues redistributed through the various recycling mechanisms across the range of scenarios. The carbon-capital tax combination generally returns the greatest portion, in some early years even exceeding carbon receipts. The carbon-labor tax swap redistributes smaller portions than does the capital tax option for all but the 1% growth tax trajectories in the years between the mid-2020's and the early-2040's; here too there are years in which more money is redistributed than is raised by taxing carbon during the years when the GDP effect is positive. The percentage recycled is least and the haircut is greatest under lump sum redistribution, and by a substantial margin. This ranking follows from

---

[9] An alternative decomposition is given by $(trate^P - trate^R) \times TBASE^R + trate^P \times (TBASE^P - TBASE^R)$ in which case the percentage recycled is $(trate^P - trate^R) \times TBASE^R / CTR$. These lack the intuitive appeal of those presented above.

the pattern of output reductions observed for the three recycling options. In Section 4 we showed how the changes in production and spending from carbon taxation are least when capital taxes are reduced, and greatest when the revenues are returned to persons as lump sums. In addition, with capital tax recycling, the capital tax base gets larger than in the no policy case while the labor tax base gets smaller. Under labor tax recycling, the opposite occurs. However, in the case of lump sum redistribution, there are no offsetting influences on these tax bases. Both the capital and labor tax bases shrink and, thus, a greater portion of carbon tax receipts must be used to restore the physical volume of government purchases than with either of the other two swap options.

Table 5.1 about here

There are other patterns worth noting in these results. Across the three recycling options, the percentages returned are larger and the haircuts smaller in the earlier years than they are in the later years under higher carbon taxes. As carbon prices rise, abatement becomes more difficult, the pressures on tax bases increase and more funds are required to preserve real government spending. Under lump sum redistribution, the percentages returned decline and haircuts increase through 2040 and then the trends slightly reverse. With capital tax recycling, there is no such reversal as there occur a systematic increase in the carbon tax haircut over time. For labor tax recycling, the pattern is mixed. Under the 1% growth scenarios, it is an inverted U with recycled percentages rising and haircuts falling and then reversing around the mid-2030s. For the 5% growth scenarios, the pattern is wave-like, following the inverted U of the other labor tax scenarios but eventually reversing again and appearing like that observed under lump sum redistribution.

Finally, there are patterns associated with the levels and growth rates of carbon taxation. For a given growth rate, 1% or 5%, it is generally the case that recycled percentages are larger and haircuts are smaller the lower the initial price, \$25 versus \$50, regardless of the recycling mechanism. Further, for a given initial price, \$25 or \$50, recycled percentages are larger and haircuts are smaller the lower the growth rate, 1% versus 5%, but only under the lump sum and labor tax mechanisms; with capital tax recycling, it is the higher growth rate of 5% that yields larger recycled percentages and smaller haircuts.

6. Household and Individual Welfare

6.1 Household Welfare

In Section 2.3, we established the link between our model of consumer behavior and the measurement of household welfare. Given household size and the distribution of household types, we also measure welfare at the individual or per person level. For each household type, we derive an expenditure function that depends on prices and utility (eq. 2.11). This lifetime expenditure is equal to full wealth, defined as tangible assets plus household time endowment. We calculate the welfare impact of carbon taxation as the equivalent variation in full wealth – how much full wealth must change at base-case prices to generate the same change in household welfare due to the carbon tax policy. In our model, where preferences differ by household type, aggregations of household equivalent variations, weighted or otherwise, *cannot* be interpreted as measures of social welfare, and we use the social expenditure function in 2.15.

There are thousands of households for each of our demographic types, each with a different income. We present equivalent variations for three possible levels of full wealth (Ω_d) for each type – the mean wealth, half the mean and twice the mean. Combining these three levels of full wealth with the 244 household types we present a total of 732 equivalent variations in response to each change in energy and environmental policy. The lowest level of full wealth that we consider is \$1.4 million in 2010 dollars, while the highest is \$58.0 million. The population-weighted average mean full wealth is \$11.7 million, while the averages at half and twice mean full wealth are \$5.8 million and \$23.4 million, respectively.

The composition of household types may be summarized as follows. Number of children: none 66%, one 14%, two 13%, 3+ 7%. Number of adults: one 35%, two 51%, 3+ 14%. Regionally: Northeast 18.9%, Midwest 23.0%, South 36.5%, West 21.6%. Location: urban 92.1%; rural 7.9%. Race and gender of head: non-white females 7.4%, white females 22.5%, non-white males 10.3%, white males 59.8%.

To summarize the changes in household full wealth for the different demographic types, we compute population-weighted averages for each combination of the household characteristics. These are shown in Tables 6.1 through 6.3 for the \$25 @ 5% carbon tax trajectory and the three revenue recycling options. The demographic conclusions from these are robust across the other carbon tax paths, differing only in scale. Again, it is important not to misinterpret these summary household measures as indicators of social welfare.

[Tables 6.1 through 6.3 about here]

Over the entire set of 732 household types and incomes, the percentage changes in full wealth from taxing carbon are not large; with changes from lump sum redistribution being the largest, and those from capital tax recycling being the smallest. With lump sum recycling, the losses in lifetime full expenditure are in the range of 0.40 to 0.52% depending on the level of wealth. Under the capital tax option, there occurs a small gain of 0.01% at the twice mean level of wealth, but on average, the losses are 0.02 and 0.05% at the mean and half mean levels, respectively. For labor tax recycling, the percentage losses in full wealth range from 0.15 to 0.16%, depending on the level of wealth. We find the variation in these percentage changes relative to their means to be greatest for the capital tax swap and least for labor tax recycling, with that for the lump sum option falling between. As evidence, the coefficient of variation at the mean level of full wealth is 1.5 under capital tax recycling, 0.7 with lump sum redistribution and 0.2 for the labor tax swap.

The averages in each row of these tables provide insights into the regressivity or progressivity of the three revenue recycling schemes. For the lump sum and capital tax options, percentage losses diminish, and-or benefits increase, as full wealth increases. This suggests that these carbon tax swaps are, on average, regressive with respect to household full wealth. With labor tax recycling, the opposite occurs – average percentage losses rise with full wealth indicating its progressivity.

We now consider the implications of household size. Under lump sum recycling and for a given number of adults, households with more children fare better than households with fewer. The relationships are a bit complicated. With no children, the percentage losses decline as the number of adults increases. With one child, the percentage losses increase with the addition of the second adult but then decline with more adults. For households with two children, there are benefits on average for single adult households with losses that decline as more adults are added. Households with three or more children fare best under lump sum recycling with single adult households benefitting and those with three or more adults marginally better off than two adult households.

Under capital tax recycling and for a given number of adults, households with fewer children fare better on average. And, for a given number of children, capital tax reductions are less costly the more adults there are. Under labor tax recycling and for a given number of children, the percentage losses in full wealth increase as the number of adults increase. For a given number of adults, there is a consistent pattern. Households with three or more children experience the largest percentage losses followed closely by childless households. Households with two children incur the smallest losses with single child households second best. Noteworthy under labor tax recycling is the lack of variability within the adult groupings.

We next turn to region of residence and household location. With lump sum redistributions, percentage losses to households in the South are smallest followed by the Midwest, Northeast and West. It is not particularly surprising that the generally poorer regions of the country – the South and Midwest – fare better under lump sum recycling than do the wealthier Northeast and West. Consistent with this regional pattern, losses on average for urban households are considerably larger than they are for rural households. Under capital tax recycling, this pattern reverses although the magnitudes of change are significantly smaller. At mean full wealth, households in the West benefit slightly with a small average loss for those in the Northeast and much larger losses for those in the Midwest and South. Now, with lower capital taxation, it is the urban households that fare better than their rural counterparts. Under labor tax recycling, there again appears a narrowing in the regional and urban-rural variation. Losses are least for households in the Midwest and South followed by the West and Northeast although, in percentage terms, the differences are not large. Urban households fare better than rural households by a similar spread.

Finally, there are the characteristics of the race and gender of the household head. For lump sum redistribution, households headed by females incur smaller percentage losses in full wealth than do households headed by males and households headed by non-whites fare better than those headed by whites. Under the capital tax swap, the female-male ordering reverses but the non-white-white ranking remains the same; male-headed households experience the smaller losses as do households headed by non-whites. With labor tax recycling, there is yet another ordering. Like lump sum, households headed by males suffer the larger percentage losses but now households headed by non-whites are at a comparative disadvantage.

6.2 Individual Welfare

Policies for compensating people for higher carbon prices are sometimes couched in terms of per capita payments instead of households. To estimate the effects of such policies we convert household full wealth and equivalent variations to those for individuals using information about household size. We noted in section 2.5 above that we have two methods of implementing a lump sum compensation scheme; one proportional to household expenditures (eq. 2.17a), and one is equal per capita (eq. 2.17b). In the cases discussed so far, we used the “head tax” approach.

The wealth characteristics for individuals calculated from our 244 household types are as follows. The lowest level of lifetime full expenditure that we consider is $425 thousand in 2010 dollars, while the highest is $20.6 million. These are our "poorest" and "richest" individuals. The population-weighted average mean full wealth for individuals is $4.9 million, while the averages at half and twice mean full wealth are $2.4 and $9.7 million, respectively.

Since these estimates are derived from household types, the quintile boundaries for individuals are not exact. Quintile 1 covers 20.1% of all individuals residing in 12.3% of all households and accounting for 10.5% of total mean full wealth. Quintile 5 covers 19.6% of all individuals residing in 26.5% of all households and accounting for 29.7% of total mean full wealth. For quintiles 2, 3, and 4, the corresponding numbers for individual quintile, household share and national wealth share are: 20.0, 12.4 and 15.0%, 20.2, 17.5 and 19.7%, and 20.1, 31.3, and 25.1%, respectively. These estimates clearly show stark differences in per capita receipts if the compensation policy were equal lump sum payments to households instead of individuals.

Table 6.4 shows the equivalent variations in lifetime full expenditure by quintile for five carbon tax paths and the three recycling options. Also shown are two tax swaps combining lump sum and capital redistribution for the $25 @ 5% scenario. The changes appear in both dollars and percentages, with lump sum the largest, capital the smallest and labor in between. As with the household averages discussed above, the spreads between the three recycling options are quite large.

[Table 6.4 about here]

The averages over individuals complicate the conclusions for regressivity and progressivity based on the averages over households. Lump sum recycling is unambiguously progressive in both dollars and percentages. Indeed, the lowest quintile actually benefits under all but the most extreme carbon tax regime. For the other quintiles, losses in dollars and as percentages of full wealth rise with rising affluence. These patterns also hold for the two blended options that include both lump sum transfers and capital tax cuts in the last four columns of Table 6.4. Purely reducing capital taxes is regressive in percentage terms with progressively declining losses for each wealthier quintile. In dollar terms, it is regressive only in the lower carbon price cases, with small losses declining as wealth increases and small gains possible for the upper quintiles. However, as carbon taxation becomes more severe, we observe progressivity in the lower four quintiles; losses rise with rising wealth. It is only between quintiles four and five that we see continuing regressivity. Labor tax recycling is progressive in dollar terms throughout the range of carbon tax paths. In percentage terms, however, it is progressive only through quintile three after which it regresses. In the 2025 & 2050 Target scenario, labor tax recycling is progressive in dollars but fully regressive in percentages.

The quintile averages for individuals, like the household averages above, result from adding full wealth and equivalent variations in it. We again emphasize that these aggregations cannot be construed as either group or societal welfare because of the nature of preferences in IGEM's household utility model. We also note the need to reconcile differences in the findings on regressivity and progressivity between the household and individual averages. The filter that resolves these issues is a social welfare function and it is to this we now turn.

7. Social Welfare Impacts

We present money-metric measures of social welfare for carbon taxation based on the functions given in equations 2.12 and 2.14. Unlike the averages above, this function allows exact aggregation over the 244 household types in full recognition of their differential preferences. Social welfare increases with increasing household welfare, and with transfers from richer to poorer households. As noted in equation 2.12, society's preference for equality is parametric ranging from the purely egalitarian view which gives the greatest weight to equity to the purely utilitarian view which gives the least weight to equity.

Equation 2.13 gives *efficient welfare* as the maximum achievable through a reallocation of lifetime expenditure. This magnitude is independent of society's aversion to inequality. *Equity welfare* is the difference between actual welfare, which depends on social preference for equality, and efficient welfare. Actual social welfare, therefore, is smaller than efficient welfare by the loss due equity welfare. The equivalent variation for a carbon tax-recycling scenario is equation 2.14, the difference between the full wealth of the social welfare due to *actual* policy and base case full wealth, both measured at base case prices and interest rates. This equivalent variation is decomposed into its efficiency and equity components in equation 2.16.

We have two inequality measures; absolute progressivity (equation 2.20) and relative progressivity (equation 2.21). A carbon tax policy is progressive in the absolute sense if the gap between actual and efficient social welfare narrows and is regressive if it widens. A carbon tax policy is progressive in the relative sense if the ratio of actual to efficient social welfare increases and is regressive if it decreases.

Table 7.1 shows the equivalent variations in social welfare and their equity-efficiency decompositions for the fifteen carbon tax-recycling option pairings under the purely egalitarian ($\mu = -1$) and purely utilitarian ($\mu = -\infty$) views. Unlike the household and individual averages in Section 6 where there are groups which gained from the carbon policy, there are only welfare losses at the societal level under exact aggregation. There are losses in efficient welfare (W_{max}) in all fifteen cases. The changes in the absolute values of equity welfare (ΔEQ) are smaller when society is least averse to inequality, i.e., under the purely utilitarian view.

[Table 7.1 about here]

Capital-tax rate recycling emerges as the clear winner in our social welfare comparisons. This option yields by far the smallest welfare burdens borne by society as its reductions of tax distortions more fully compensate the economic costs of carbon taxes. While its comparative advantage diminishes with increasingly aggressive carbon-tax structures, it has a very small loss under the low carbon price regimes. The major disadvantage of incentivizing new capital formation is its regressivity. The capital tax swap is regressive in the relative sense under all carbon tax paths. Like the quintile averages in Section 6, it also is regressive in the absolute sense until the rates of carbon taxation reach their highest levels. At this point, there is not only an erosion in capital tax's comparative advantage but also a transition to its becoming progressive in the absolute sense.

Labor-tax recycling is progressive in both the absolute and relative senses under both the egalitarian and utilitarian views. Losses in social welfare are much larger than those under the capital tax option due to the labor tax bias against saving and investment, and the increased willingness of households and individuals to sacrifice leisure prompted by real-wage incentives.

Also, less of the carbon tax receipts are recycled under this scheme as compared to capital tax recycling.

Lump-sum redistribution results in the largest societal welfare losses among the three swap options. Under this pairing, the economic impacts of carbon taxation are large and non-offsetting for labor and capital. Consequently, the policy haircut is the largest. With only income effects and no relative price effects like those found under capital or labor tax recycling, the increases in leisure are insufficient compensation for the greater economic losses. Lump sum redistribution provides the largest gains in equity welfare and is progressive in the absolute sense under all carbon tax regimes and in both egalitarian and utilitarian views. This matches the conclusion from the quintile analysis of individuals. However, lump sum recycling is societally regressive in the relative sense under these same regimes and equity views. The improvements in equality, large as they are, are not enough to improve society's relative welfare ranking because they do not more fully compensate the large losses in welfare efficiency.

There is no double dividend for social welfare among these scenarios. However, the conclusions above make clear the possibility of designing a carbon tax and revenue recycling scheme that holds the poorest among us harmless, is progressive to some extent for society, and results in small sacrifices in economic welfare to the benefit of the environment. Progressivity requires some combination of lump sum and labor tax recycling while reducing losses in social welfare requires more extensive use of the capital tax option.

As further evidence of the capital tax advantage, Figure 7.1 shows the loss in efficient welfare, expressed as a welfare cost, per unit of cumulative abatement from 2015 through 2130. For the four tax-and-growth scenarios, the welfare cost of abatement ranges from $0.19 to $3.90 per ton with capital tax recycling. The welfare cost per ton increases to $11.21 in the 2025 & 2050 Targets case. For labor tax recycling, the range is $11.09 to $16.49 per ton with a cost of $26.39 under the 2025 & 2050 Targets regime. With lump sum redistribution, the range is $37.15 to $43.61 per ton and $55.31 per ton in the 2025 & 2050 Targets scenario. Across all five carbon tax paths, the per ton welfare costs of abatement under capital tax recycling average only 7.6% of those under lump sum recycling and only 18.5% of those under the labor tax option. Again, promoting capital formation is the best use of carbon tax revenues in terms of reducing the magnitudes of welfare losses while the lump sum and labor tax options are the best uses for reducing inequality.

[Figure 7.1 about here]

8. Contrast between Demand-side and Supply-side Emissions Modeling

Large scale multi-sector models such as those used in the EMF studies almost always use a simplified single-market representation of the commodity markets. That is, they assume there is one price, and one variety, of each commodity identified in the model, abstracting from the fact, for example, that there are many varieties of coal sold at different prices, or different contracts or uses for different buyers of the same good.

For CO_2 accounting and modeling of carbon prices, the reality of different prices of coal paid by different buyers is a serious challenge. In Section 2.2, we discuss how the simplified one-variety representation in equation 2.5 would result in a big difference from actual tons of coal used. In such a setting, the carbon price would be placed on the average coal and that would be equivalent to taxing the supplier of coal who sells at a price calibrated to equal the actual average price. We call this "supply-side emissions modeling". In IGEM, we recognize the different prices actually paid by using equation 2.3, i.e. recognizing that the electric utility sector pays much cheaper prices for a ton of coal than does, say, the primary metals sector for it metallurgical coal. The carbon price is represented by a tax on the actual tons purchased by each buyer (AA_{ijt} in equation 2.3 is the quantity used by j) and we call this "demand-side" modeling. This approach means that the tax per ton CO_2 applied equally to all tons of coal results in a different percentage change in the price of coal input for different purchasers.

Similar issues arise with the pricing and uses of gas and oil. Residential, commercial, industrial, transport, utility and foreign buyers pay different prices for the same combustible natural gas. The economy uses a wide variety of refined petroleum products, each with its own pricing structure and array of applications. Moreover, the transactional uses of gas and oil are not limited to combustion; there are input and feedstock considerations as well as export sales, which are also true for coal. In demand-side emissions modeling, we can account for these differences in pricing and can isolate taxable uses even though commodities are of the one-price, homogeneous variety. In supply-side emissions modeling, all buyers face an economy-wide average carbon price and homogeneity extends to emissions.

To illustrate the magnitude of the difference in the two approaches we repeated the \$25 @ 5% scenario using supply-side emissions modeling, that is, taxing the suppliers of fossil fuels so that all purchasers suffer the same percentage change in prices. The impact on emissions and other key variables from the two approaches are compared in Table 8.1. We discuss only the impacts for the capital tax and labor tax recycling cases here.

[Table 8.1 about here]

We begin by focusing on the tax shifting that occurs under the supply-side approach. Reductions in coal use are comparable across the two approaches. However, the supply-side approach imposes a lighter tax burden on the coal price paid by electric utilities but a heavier one on other users like primary metals. This causes smaller reductions in coal-based generation compared to the demand-side approach but larger reductions in primary metals output. At an economy-wide carbon tax rate, the primary metals sector faces a much higher burden on its comparatively less-elastic coal use which results in much larger demand and output losses. Reductions in petroleum product use are smaller under the supply-side approach. Homogeneous carbon pricing means that some petroleum users bear heavier burdens while others bear lighter burdens than occur under demand-side emissions attributions. For natural gas, the burdens are shifted not only within the mining and utility sectors but also across them. Output reductions are smaller for gas mining but larger for gas utilities. In the case of gas mining, electric utilities face a lower gas price while all other buyers, including gas utilities, face a higher one. Like petroleum product users, some gas utility customers face higher prices and others lower prices than under the demand-side approach. As examples of the impacts of this tax shifting for the purchasers of petroleum and gas, the chemicals, rubber and plastics industries experience larger output reductions as their inputs are more expensive while output losses in commercial transportation are smaller as their inputs are less so.

Under capital tax recycling, the change in coal mining output is -22%, similar to the demand-side approach, but gas mining output is -7.9% versus -9.4%, gas mining output is -9.1% versus -8.0%, and petroleum output is -5.1% versus 6.5%. The impact of electric utilities is most notable, -4.2% versus -7.2%; that is, the coal and gas reductions in the demand-side approach are borne more by electric utilities which get cheaper coal and gas, compared to the supply-side approach where the other users of coal and gas bear a bigger share of the burden. Under labor tax recycling, the change in coal mining output is a similar -23%, while gas mining output is -7.8% versus -9.2%, gas mining output is -9.0% versus -7.9%, petroleum output is -4.6% versus 6.1%, and electric utilities is -3.6% versus -6.6%. The net effect of this tax shitting is that the cumulative abatement of CO_2 emissions is only about 22 Gt in the supply-side approach compared to the more than 40 Gt under demand-side modeling.

In the capital tax recycling scenarios, the GDP change (over 2015-50) is now 0.46% compared to 0.20%; there is a bigger double dividend under the supply-side approach. Consumption benefits as average losses of 0.46% in the demand-side approach are now gains averaging 0.14%. The impact on investment and capital formation is even more favorable leading to smaller reductions in labor supply, smaller increases in leisure demand and increases in full consumption. Perhaps, more important are differences in the terms-of-trade effects under the two emissions approaches. In the demand-side-capital-tax case, they deteriorate, i.e., the dollar weakens, and import reductions exceed export reductions. In the supply-side-capital-tax scenario, the terms-of-trade improve. Imports increase with the stronger economy and exports fall further under the influence of the stronger dollar. The demand-supply contrast for labor tax recycling is equally dramatic. The GDP change is now a positive 0.05% compared to a -0.06% in the demand-side approach. This consists of a bigger average gain in consumption from 0.32% to 1.01% and a smaller loss in investment from 0.78% to 0.48%. Labor-leisure choice further favors labor over leisure but consumption compensates yielding a small average gain in full consumption. Under the supply-side approach, there is even a bigger improvement in the terms-of-trade from labor tax recycling. Imports increase although less than occur with the capital tax swap while export reductions are almost double those from the demand-side approach.

The change from demand-side to supply-side emissions modeling has a positive impact on social welfare. Using the egalitarian form, social welfare under capital tax recycling increases by $2,134 billion versus a demand-side loss of $274 billion. The gain in efficiency is $2,835 billion while the loss due to increased inequality is $427 billion. Under labor tax recycling, social welfare rises by $798 billion compared to a demand-side loss of 1395 billion. This difference in social welfare consists of an increase in the efficiency component of $2,476 billion but a reduction in the equity component of $282 billion. Under the supply-side approach, capital tax recycling is regressive in the absolute sense but progressive in the relative sense; with demand-side modeling, it is regressive in both metrics. Labor tax recycling remains progressive in both senses under both emissions treatments. Unfortunately, the dividends in social welfare arising from a supply-side tax design come at the expense of higher emissions and lower abatement[11].

These results indicate that one should take great care to specify clearly the modeling assumptions about emissions accounting. A common average price approach understates the negative impacts by not recognizing that sectors that pay below (above) average prices in the actual economy suffer more (less) from a carbon tax. Moreover, the dividends in social welfare

---

[11] We also considered lump sum recycling under supply-side emissions modeling; it remains the least favorable outcome in terms of social welfare, with losses around three quarters of those from the demand-side approach but similar equity gains. Thus, the lump sum option is progressive, both absolutely and relatively. For comparable GDP effects, consumption and import reductions are almost halved while export reductions increase by nearly fifty percent with the supply-side approach. Cumulative abatement is in line with the capital and labor tax supply-side scenarios.

arising from a supply-side tax design versus a demand-side scheme come at the expense of higher emissions and lower abatement for the same carbon tax.

9. Summary and Conclusions

For the Energy Modeling Forum's assessment of US policies on carbon taxation and revenue recycling (EMF 32), we applied a new version of our Intertemporal General Equilibrium Model (IGEM) based on the North American Industry Classification System (NAICS). We simulated the impacts arising from a broad range of carbon taxes and three revenue recycling options – lump sum redistributions, capital tax reductions, and labor tax cuts. We followed the path from the introduction of a carbon tax-and-swap pairing to their effects on industry prices and quantities, and then considered their macroeconomic consequences from both the demand-expenditure and supply-income perspectives. We offered a dynamic view of the so-called "haircut" that arises from the general equilibrium consequences of a carbon-tax-and-swap pairing and limits the amount of revenues recyclable from the swap. Finally, we examined the welfare implications of these pairings for households, individuals, and society, the latter in terms of efficiency and equity.

In IGEM, we find CO_2 emissions abatement increases at a decreasing rate both over time and with the increasing severity of carbon taxation. While the economic and welfare outcomes for the uses of carbon tax receipts vary greatly across the three recycling options, we find the consequences for energy and emissions reductions do not. This means that policy makers need not compromise their environmental objectives when designing carbon tax swap options.

Reducing capital taxes promotes new saving, investment and capital formation and is the preferred recycling mechanism. It favors the capital goods industries, results in the least damage to the overall economy, allows the largest percentages of carbon tax revenues to be recycled, and secures the smallest losses in household, individual and societal welfare. In 2010 dollars, the social welfare efficiency loss per ton abated ranges from \$0.19 to \$11.21 depending on the path of carbon prices. The only drawback to capital tax recycling is its regressivity. We find it to be regressive in full wealth at all but the highest rates of carbon taxation.

Reducing labor taxes promotes consumption and work through real-wage incentives and is the next most favorable recycling scheme. It favors the consumer sectors but with greater damage to the overall economy, larger revenue "haircuts," and bigger welfare losses. Here, the welfare loss per ton abated ranges from \$11.09 to \$26.39 depending on the carbon tax trajectory. The benefit from labor tax recycling is that it is unambiguously progressive for households, individuals, and society at all levels of carbon pricing.

The lump sum redistribution of carbon tax revenues is the least favorable recycling option. It incentivizes neither capital nor labor. Consequently, the damages to the economy and welfare are the greatest among the three schemes and the returned percentages of carbon tax receipts are the smallest. Under the lump sum treatment, the welfare loss per ton abated ranges from \$37.15 to \$55.31 as carbon taxation becomes more aggressive. While the welfare losses are the largest, this option, like labor tax recycling, is an instrument for greater equality. Though regressive in the relative sense, lump sum redistributions are progressive in the absolute sense and provide the best means for holding the poorest harmless from the welfare consequences of carbon taxation.

For capital and labor tax recycling, the losses in social welfare can be countered through a tax design that focusses on fossil fuel supplies and covers all uses at an economy-wide average burden. Strictly speaking, this is not a true double dividend since the social welfare gains are accompanied by smaller emissions reductions for a given carbon tax.

In the absence of a double dividend for society and the environment, the goal would be to construct a carbon tax recycling scheme that strikes an acceptable balance between losses for the former and gains for the latter while protecting the poor and improving overall equality. This should be achievable since we find welfare losses of only 1% of lifetime wealth even under the high carbon price scenarios.

Table 1.1
Carbon Tax Scenarios
$(2010) per metric tonne CO_2 equivalent ($mtCO_2$-e)

			Transition to Steady State	
Scenario Title	Tax in 2020	Growth Rate	Year	Tax
EMF Specified Tax Paths				
$25 @ 1%	$25.00	1.00%	2050	$33.70
$25 @ 5%	$25.00	5.00%	2050	$108.05
$50 @ 1%	$50.00	1.00%	2050	$67.39
$50 @ 5%	$50.00	5.00%	2050	$216.10
Social Cost of Carbon (SCC)	$44.00	Varied	2050	$72.00
IGEM Determined Tax Paths				
Clean Power Plan (CPP) Match	$9.48	5.00%	2030	$15.45
2025 Target	$19.02	5.00%	2050	$82.21
2025 & 2050 Targets	$11.54	16.04%	2050	$1,000.00

Table 3.1

Cumulative CO2 Emissions from Fossil Fuel Combustion

Gigatonnes CO2 (GtCO2), economy wide 2015-2050

	Revenue Recycling Option			
Scenario Title	Lump Sum	Capital	Labor	Lump Sum & Capital
Cumulative Emissions				
Base Case	194.4	194.4	194.4	194.4
$25 @ 1%	167.1	167.7	168.3	--
$25 @ 5%	152.8	153.7	154.0	153.1
$50 @ 1%	150.2	151.0	151.7	--
$50 @ 5%	131.9	133.0	133.2	--
Social Cost of Carbon (SCC)	150.9	--	--	--
Clean Power Plan (CPP) Match	183.9	--	--	--
2025 Target	159.8	--	--	--
2025 & 2050 Targets	127.5	129.0	128.0	--
Cumulative Abatement				
$25 @ 1%	27.3	26.7	26.1	--
$25 @ 5%	41.6	40.7	40.4	41.3
$50 @ 1%	44.2	43.4	42.7	--
$50 @ 5%	62.5	61.4	61.2	--
Social Cost of Carbon (SCC)	43.5	--	--	--
Clean Power Plan (CPP) Match	10.5	--	--	--
2025 Target	34.6	--	--	--
2025 & 2050 Targets	66.9	65.4	66.4	--

Table 4.1
Impacts on commodity prices for different tax levels (lump sum redistribution)
Average percent change from base, 2015-2050.

Lump Sum Redistribution	$25 @ 1%	$25 @ 5%	$50 @ 1%	$50 @ 5%	2025&2050 Targets
Agriculture	0.66	1.13	1.24	2.04	2.73
Oil mining	-1.05	-1.88	-2.00	-3.38	-4.50
Gas mining	1.59	2.85	2.99	5.02	6.81
Coal mining	20.58	32.33	36.54	55.18	70.28
Non-energy mining	0.82	1.44	1.55	2.65	3.86
Electric utilities	7.01	11.64	12.56	19.91	25.35
Gas utilities	5.91	11.18	11.88	22.43	46.43
Water and wastewater	0.37	0.61	0.69	1.07	1.20
Construction	0.43	0.72	0.80	1.32	1.78
Wood and paper	0.83	1.43	1.54	2.59	3.61
Non-metal mineral products	1.06	1.85	2.00	3.41	4.97
Primary metals	1.11	1.92	2.08	3.51	5.13
Fabricated metal products	0.58	0.95	1.07	1.69	2.12
Machinery	0.59	1.00	1.08	1.75	2.30
Information technology equipment	0.47	0.79	0.84	1.33	1.68
Electrical equipment	0.49	0.82	0.88	1.41	1.80
Motor vehicles and parts	0.58	0.99	1.06	1.72	2.28
Other transportation equipment	0.47	0.78	0.85	1.36	1.71
Miscellaneous manufacturing	0.47	0.80	0.85	1.38	1.82
Food, beverage and tobacco	0.65	1.10	1.20	1.97	2.59
Textiles, apparel and leather	0.57	0.96	1.01	1.63	2.16
Printing and related activities	0.43	0.70	0.79	1.25	1.49
Petroleum and coal products	5.00	8.89	9.70	16.87	27.53
Chemicals, rubber and plastics	0.65	1.11	1.21	1.98	2.63
Wholesale trade	0.32	0.52	0.58	0.91	1.03
Retail trade	0.34	0.55	0.62	0.95	1.06
Transportation and warehousing	1.40	2.45	2.68	4.55	6.46
Publishing, broadcasting, telecommunications	0.34	0.55	0.62	0.95	0.99
Software & information technology services	0.33	0.54	0.60	0.93	1.07
Finance and insurance	0.33	0.53	0.60	0.91	0.93
Real estate and leasing	0.46	0.71	0.82	1.23	1.19
Business services	0.25	0.40	0.46	0.70	0.77
Educational services	0.32	0.53	0.59	0.94	1.18
Health care and social assistance	0.31	0.51	0.57	0.89	1.03
Accommodation and other services	0.38	0.62	0.69	1.08	1.30
Other government	0.31	0.52	0.59	0.95	1.20

Table 4.2
Impacts on commodity prices for different recycling options ($25 @5% case)
Average percent change from base, 2015-2050.

$25 @ 5% Under Recycling Option	Lump Sum	Capital Tax	Labor Tax
Agriculture	1.13	0.44	-0.77
Oil mining	-1.88	-1.89	-3.44
Gas mining	2.85	2.85	1.51
Coal mining	32.33	31.14	30.21
Non-energy mining	1.44	0.88	-0.53
Electric utilities	11.64	10.89	9.79
Gas utilities	11.18	10.63	9.51
Water and wastewater	0.61	-0.10	-1.34
Construction	0.72	0.38	-1.40
Wood and paper	1.43	0.89	-0.57
Non-metal mineral products	1.85	1.44	-0.20
Primary metals	1.92	1.55	-0.13
Fabricated metal products	0.95	0.51	-1.09
Machinery	1.00	0.53	-1.01
Information technology equipment	0.79	0.45	-1.27
Electrical equipment	0.82	0.44	-1.22
Motor vehicles and parts	0.99	0.67	-1.08
Other transportation equipment	0.78	0.33	-1.28
Miscellaneous manufacturing	0.80	0.42	-1.26
Food, beverage and tobacco	1.10	0.51	-0.87
Textiles, apparel and leather	0.96	0.74	-1.10
Printing and related activities	0.70	0.25	-1.37
Petroleum and coal products	8.89	8.62	7.22
Chemicals, rubber and plastics	1.11	0.58	-0.84
Wholesale trade	0.52	-0.05	-1.51
Retail trade	0.55	0.02	-1.52
Transportation and warehousing	2.45	2.00	0.42
Publishing, broadcasting, telecommunications	0.55	-0.19	-1.38
Software & information technology services	0.54	0.06	-1.53
Finance and insurance	0.53	-0.21	-1.40
Real estate and leasing	0.71	-0.35	-1.03
Business services	0.40	-0.08	-1.66
Educational services	0.53	0.04	-1.53
Health care and social assistance	0.51	0.03	-1.56
Accommodation and other services	0.62	0.13	-1.44
Other government	0.52	0.02	-1.51

Table 4.3
Impacts on final demand quantities for different recycling options
Average percent change from base, 2015-2050.

Under Recycling Option	Lump Sum	Capital Tax	Labor Tax
$25 @ 1%			
GDP	-0.68	0.07	0.17
Consumption	-0.60	-0.25	0.36
Investment	-1.20	0.62	-0.05
Government	0.00	0.00	0.00
Exports	-1.40	-0.18	-0.58
Imports	-1.29	-0.36	-0.38
$25 @ 5%			
GDP	-1.16	0.20	-0.06
Consumption	-0.98	-0.46	0.32
Investment	-2.14	1.32	-0.78
Government	0.00	0.00	0.00
Exports	-2.41	-0.22	-1.38
Imports	-2.34	-0.65	-1.15
$50 @ 1%			
GDP	-1.25	0.03	0.20
Consumption	-1.11	-0.54	0.53
Investment	-2.11	0.96	-0.19
Government	0.00	0.00	0.00
Exports	-2.56	-0.49	-1.20
Imports	-2.27	-0.69	-0.74
$50 @ 5%			
GDP	-2.02	0.15	-0.19
Consumption	-1.75	-0.92	0.39
Investment	-3.50	1.98	-1.24
Government	0.00	0.00	0.00
Exports	-4.15	-0.69	-2.49
Imports	-3.84	-1.18	-1.93
2025 & 2050 Targets			
GDP	-2.45	0.77	-1.13
Consumption	-2.11	-1.20	-0.36
Investment	-4.34	4.39	-3.18
Government	0.00	0.00	0.00
Exports	-5.14	-0.07	-4.09
Imports	-5.20	-1.25	-3.84

Table 4.4

Impacts on capital, labor, leisure and full consumption quantities for different recycling options

Average percent change from base, 2015-2050.

Under Recycling Option	Lump Sum	Capital Tax	Labor Tax
$25 @ 1%			
Capital stock	-0.74	0.49	-0.18
Labor demand and supply	-0.45	-0.13	0.58
Leisure demand	0.18	0.05	-0.23
Full consumption	-0.06	0.01	-0.05
$25 @ 5%			
Capital stock	-1.16	0.94	-0.67
Labor demand and supply	-0.79	-0.14	0.73
Leisure demand	0.32	0.05	-0.29
Full consumption	-0.09	-0.01	-0.12
$50 @ 1%			
Capital stock	-1.31	0.77	-0.39
Labor demand and supply	-0.78	-0.24	0.98
Leisure demand	0.32	0.10	-0.40
Full consumption	-0.13	-0.01	-0.12
$50 @ 5%			
Capital stock	-1.91	1.45	-1.08
Labor demand and supply	-1.30	-0.27	1.22
Leisure demand	0.53	0.10	-0.49
Full consumption	-0.19	-0.07	-0.25
2025 & 2050 Targets			
Capital stock	-1.73	2.93	-2.02
Labor demand and supply	-1.71	0.09	0.93
Leisure demand	0.69	-0.05	-0.36
Full consumption	-0.17	-0.17	-0.42

Table 4.5
Impacts on domestic output quantities for different tax levels (lump sum redistribution)
Average percent change from base, 2015-2050.

Lump Sum Redistribution	$25 @ 1%	$25 @ 5%	$50 @ 1%	$50 @ 5%	2025&2050 Targets
Agriculture	-0.90	-1.55	-1.70	-2.80	-3.75
Oil mining	-2.63	-4.47	-4.86	-7.87	-9.87
Gas mining	-5.87	-9.65	-10.32	-15.73	-17.78
Coal mining	-16.33	-23.66	-25.20	-33.82	-34.81
Non-energy mining	-1.60	-2.76	-2.79	-4.55	-5.74
Electric utilities	-4.73	-7.65	-8.18	-12.43	-14.65
Gas utilities	-4.94	-8.65	-9.24	-15.38	-19.96
Water and wastewater	-1.56	-2.63	-2.83	-4.57	-5.98
Construction	-1.02	-1.82	-1.79	-3.00	-3.85
Wood and paper	-1.47	-2.56	-2.71	-4.51	-5.94
Non-metal mineral products	-2.20	-3.86	-4.04	-6.76	-9.08
Primary metals	-2.19	-3.81	-3.97	-6.56	-8.72
Fabricated metal products	-1.30	-2.20	-2.32	-3.70	-4.47
Machinery	-1.40	-2.43	-2.46	-4.03	-5.00
Information technology equipment	-0.76	-1.32	-1.33	-2.18	-2.61
Electrical equipment	-0.86	-1.52	-1.52	-2.51	-3.02
Motor vehicles and parts	-1.38	-2.42	-2.45	-4.03	-5.11
Other transportation equipment	-0.64	-1.13	-1.17	-1.93	-2.38
Miscellaneous manufacturing	-0.97	-1.73	-1.74	-2.89	-3.60
Food, beverage and tobacco	-0.63	-1.07	-1.17	-1.92	-2.56
Textiles, apparel and leather	-1.00	-1.73	-1.85	-3.06	-4.01
Printing and related activities	-0.44	-0.72	-0.81	-1.23	-1.24
Petroleum and coal products	-4.16	-7.04	-7.65	-12.30	-15.18
Chemicals, rubber and plastics	-1.17	-2.01	-2.16	-3.54	-4.50
Wholesale trade	-0.63	-1.09	-1.12	-1.80	-2.13
Retail trade	-0.75	-1.30	-1.34	-2.16	-2.63
Transportation and warehousing	-2.66	-4.55	-4.84	-7.87	-10.00
Publishing, broadcasting, telecommunications	-0.54	-0.91	-0.97	-1.54	-1.78
Software & information technology services	-0.81	-1.43	-1.42	-2.31	-2.74
Finance and insurance	-0.59	-0.99	-1.08	-1.71	-2.05
Real estate and leasing	-0.82	-1.32	-1.46	-2.18	-2.15
Business services	-0.81	-1.40	-1.47	-2.39	-2.99
Educational services	0.23	0.40	0.41	0.68	0.93
Health care and social assistance	-0.33	-0.56	-0.63	-1.03	-1.39
Accommodation and other services	-0.66	-1.11	-1.21	-1.97	-2.64
Other government	-0.05	-0.09	-0.09	-0.17	-0.25

Table 4.6
Impacts on domestic output quantities for different recycling options ($25 @5% case)
Average percent change from base, 2015-2050.

$25 @ 5% Under Recycling Option	Lump Sum	Capital Tax	Labor Tax
Agriculture	-1.55	-0.77	0.01
Oil mining	-4.47	-4.16	-3.82
Gas mining	-9.65	-9.36	-9.19
Coal mining	-23.66	-22.15	-23.26
Non-energy mining	-2.76	0.49	-1.56
Electric utilities	-7.65	-7.16	-6.64
Gas utilities	-8.65	-7.97	-7.86
Water and wastewater	-2.63	-2.40	-1.43
Construction	-1.82	0.64	-0.61
Wood and paper	-2.56	-0.91	-1.41
Non-metal mineral products	-3.86	-1.86	-2.81
Primary metals	-3.81	-1.29	-2.76
Fabricated metal products	-2.20	0.13	-1.06
Machinery	-2.43	0.73	-1.25
Information technology equipment	-1.32	0.90	-0.31
Electrical equipment	-1.52	1.13	-0.40
Motor vehicles and parts	-2.42	0.46	-1.15
Other transportation equipment	-1.13	0.54	-0.36
Miscellaneous manufacturing	-1.73	1.05	-0.34
Food, beverage and tobacco	-1.07	-0.77	0.69
Textiles, apparel and leather	-1.73	-0.87	0.13
Printing and related activities	-0.72	0.32	0.47
Petroleum and coal products	-7.04	-6.49	-6.10
Chemicals, rubber and plastics	-2.01	-0.36	-0.73
Wholesale trade	-1.09	0.48	0.47
Retail trade	-1.30	0.36	0.49
Transportation and warehousing	-4.55	-3.37	-3.33
Publishing, broadcasting, telecommunications	-0.91	0.39	0.22
Software & information technology services	-1.43	0.89	-0.29
Finance and insurance	-0.99	-0.19	0.18
Real estate and leasing	-1.32	0.78	-0.68
Business services	-1.40	-0.17	-0.15
Educational services	0.40	0.37	0.76
Health care and social assistance	-0.56	-0.64	0.76
Accommodation and other services	-1.11	-1.13	0.31
Other government	-0.09	-0.01	0.02

Table 5.1

Recycled Percentage of Carbon Tax Revenues

	2020	2025	2030	2035	2040	2045	2050
Lump Sum Redistribution							
$25 @ 1%	72.4%	66.8%	64.0%	62.2%	61.8%	62.3%	63.2%
$25 @ 5%	70.8%	65.8%	63.6%	62.1%	61.8%	62.2%	62.8%
$50 @ 1%	71.2%	65.9%	63.5%	62.0%	61.9%	62.5%	63.3%
$50 @ 5%	70.5%	65.5%	63.3%	61.9%	61.4%	61.7%	61.9%
Capital Tax Recycling							
$25 @ 1%	100.8%	99.0%	96.7%	94.0%	92.2%	91.4%	90.5%
$25 @ 5%	106.2%	104.2%	101.7%	98.5%	96.0%	93.5%	89.8%
$50 @ 1%	99.6%	97.2%	94.8%	92.3%	90.9%	90.4%	89.8%
$50 @ 5%	104.7%	102.3%	99.7%	96.7%	94.3%	92.1%	88.8%
Labor Tax Recycling							
$25 @ 1%	92.7%	102.6%	101.3%	97.5%	93.6%	90.2%	88.5%
$25 @ 5%	83.8%	92.4%	90.7%	86.8%	83.5%	82.0%	84.9%
$50 @ 1%	91.3%	100.9%	99.7%	96.0%	92.1%	89.0%	87.2%
$50 @ 5%	83.8%	92.5%	90.9%	87.2%	83.8%	82.0%	83.3%

Table 6.1

Household Effects, $25 @ 5%, Lump Sum Redistribution

Weighted-averages of household equivalent variations as a % of full wealth

	Full Wealth		
	Mean	Half Mean	Twice Mean
Children, Adults per household			
3+, 3+	0.030%	-0.028%	0.088%
2, 3+	-0.133%	-0.191%	-0.075%
1, 3+	-0.309%	-0.367%	-0.251%
0, 3+	-0.461%	-0.519%	-0.404%
3+, 2	0.020%	-0.038%	0.078%
2, 2	-0.191%	-0.249%	-0.133%
1, 2	-0.379%	-0.436%	-0.321%
0, 2	-0.580%	-0.638%	-0.522%
3+, 1	1.029%	0.970%	1.087%
2, 1	0.336%	0.278%	0.394%
1, 1	-0.202%	-0.260%	-0.145%
0, 1	-0.701%	-0.759%	-0.643%
Region of household			
Northeast	-0.500%	-0.557%	-0.442%
Midwest	-0.446%	-0.504%	-0.388%
South	-0.417%	-0.475%	-0.359%
West	-0.508%	-0.566%	-0.451%
Race & gender of household head			
Non-white female	-0.145%	-0.203%	-0.087%
White female	-0.462%	-0.520%	-0.405%
Non-white male	-0.386%	-0.444%	-0.328%
White male	-0.509%	-0.567%	-0.451%
Location of household			
Urban	-0.474%	-0.532%	-0.416%
Rural	-0.284%	-0.342%	-0.226%
Overall	-0.459%	-0.517%	-0.401%

Table 6.2
Household Effects, $25 @ 5%, Capital Tax Recycling
Weighted-averages of household equivalent variations as a % of full wealth

	Full Wealth		
	Mean	Half Mean	Twice Mean
Children, Adults per household			
3+, 3+	-0.036%	-0.069%	-0.004%
2, 3+	-0.033%	-0.065%	0.000%
1, 3+	-0.019%	-0.051%	0.013%
0, 3+	0.004%	-0.028%	0.036%
3+, 2	-0.044%	-0.077%	-0.012%
2, 2	-0.035%	-0.067%	-0.002%
1, 2	-0.027%	-0.059%	0.006%
0, 2	-0.007%	-0.040%	0.025%
3+, 1	-0.071%	-0.104%	-0.039%
2, 1	-0.061%	-0.093%	-0.029%
1, 1	-0.046%	-0.079%	-0.014%
0, 1	-0.026%	-0.058%	0.007%
Region of household			
Northeast	-0.001%	-0.033%	0.032%
Midwest	-0.032%	-0.065%	0.000%
South	-0.043%	-0.075%	-0.010%
West	0.007%	-0.026%	0.039%
Race & gender of household head			
Non-white female	-0.025%	-0.057%	0.007%
White female	-0.030%	-0.063%	0.002%
Non-white male	-0.008%	-0.040%	0.025%
White male	-0.020%	-0.053%	0.012%
Location of household			
Urban	-0.016%	-0.048%	0.016%
Rural	-0.089%	-0.121%	-0.056%
Overall	-0.022%	-0.054%	0.011%

Table 6.3
Household Effects, $25 @ 5%, Labor Tax Recycling
Weighted-averages of household equivalent variations as a % of full wealth

	Full Wealth		
	Mean	Half Mean	Twice Mean
Children, Adults per household			
3+, 3+	-0.204%	-0.198%	-0.210%
2, 3+	-0.192%	-0.186%	-0.198%
1, 3+	-0.198%	-0.192%	-0.203%
0, 3+	-0.203%	-0.197%	-0.209%
3+, 2	-0.168%	-0.162%	-0.173%
2, 2	-0.158%	-0.152%	-0.164%
1, 2	-0.161%	-0.155%	-0.167%
0, 2	-0.165%	-0.160%	-0.171%
3+, 1	-0.119%	-0.113%	-0.125%
2, 1	-0.106%	-0.100%	-0.111%
1, 1	-0.111%	-0.105%	-0.116%
0, 1	-0.112%	-0.106%	-0.118%
Region of household			
Northeast	-0.155%	-0.149%	-0.161%
Midwest	-0.148%	-0.142%	-0.154%
South	-0.149%	-0.143%	-0.155%
West	-0.152%	-0.147%	-0.158%
Race & gender of household head			
Non-white female	-0.151%	-0.145%	-0.157%
White female	-0.123%	-0.117%	-0.129%
Non-white male	-0.181%	-0.175%	-0.186%
White male	-0.156%	-0.150%	-0.162%
Location of household			
Urban	-0.150%	-0.144%	-0.156%
Rural	-0.156%	-0.150%	-0.161%
Overall	-0.151%	-0.145%	-0.157%

Table 6.4 Individual Effects, Mean Full Wealth

Weighted-averages of individual equivalent variations as a % of mean full wealth

							Equiproportional		50-50 Outcome	
	Lump Sum		Capital Tax		Labor Tax		Lump Sum & Capital		Lump Sum & Capital	
	$(2010) Bn	% Change	$(2010) Bn	% Change	$(2010) Bn	% Change	$(2010) Bn	% Change	$(2010) Bn	% Change
$25 @ 1%										
Quintile 1	170	0.10%	-29	-0.02%	-105	-0.06%				
Quintile 2	-226	-0.10%	-20	-0.01%	-162	-0.07%				
Quintile 3	-591	-0.19%	-15	-0.01%	-232	-0.08%				
Quintile 4	-1,127	-0.29%	1	0.00%	-247	-0.06%				
Quintile 5	-1,498	-0.32%	53	0.01%	-322	-0.07%				
$50 @ 1%										
Quintile 1	265	0.16%	-79	-0.05%	-219	-0.13%				
Quintile 2	-437	-0.19%	-71	-0.03%	-329	-0.14%				
Quintile 3	-1,084	-0.35%	-68	-0.02%	-459	-0.15%				
Quintile 4	-2,039	-0.52%	-55	-0.01%	-505	-0.13%				
Quintile 5	-2,694	-0.58%	35	0.01%	-640	-0.14%				
$25 @ 5%										
Quintile 1	183	0.11%	-86	-0.05%	-263	-0.16%	98	0.06%	59	0.04%
Quintile 2	-579	-0.25%	-77	-0.03%	-388	-0.16%	-367	-0.16%	-323	-0.14%
Quintile 3	-1,282	-0.42%	-75	-0.02%	-530	-0.17%	-798	-0.26%	-676	-0.22%
Quintile 4	-2,326	-0.59%	-58	-0.01%	-602	-0.15%	-1,432	-0.36%	-1,197	-0.30%
Quintile 5	-3,031	-0.65%	42	0.01%	-748	-0.16%	-1,828	-0.39%	-1,504	-0.32%
$50 @ 5%										
Quintile 1	232	0.14%	-218	-0.13%	-514	-0.31%				
Quintile 2	-1,028	-0.44%	-224	-0.10%	-743	-0.31%				
Quintile 3	-2,187	-0.71%	-239	-0.08%	-996	-0.32%				
Quintile 4	-3,922	-1.00%	-252	-0.06%	-1,157	-0.29%				
Quintile 5	-5,075	-1.09%	-93	-0.02%	-1,402	-0.30%				
2025 & 2050 Targets										
Quintile 1	-356	-0.22%	-736	-0.45%	-1,336	-0.81%				
Quintile 2	-2,461	-1.04%	-857	-0.36%	-1,848	-0.78%				
Quintile 3	-4,395	-1.43%	-976	-0.32%	-2,365	-0.77%				
Quintile 4	-7,366	-1.87%	-1,191	-0.30%	-2,920	-0.74%				
Quintile 5	-9,213	-1.98%	-956	-0.21%	-3,346	-0.72%				

Table 7.1
Social Welfare Effects
Welfare changes in $(2010) Billions

	Egalitarian			Utilitarian		
	Lump Sum	Capital Tax Rate	Labor Tax Rates	Lump Sum	Capital Tax Rate	Labor Tax Rates
$25 @ 1%						
Due to equity	$695	-$26	$409	$244	-$6	$174
Due to efficiency	-$3,155	-$16	-$896	-$3,155	-$16	-$896
Total	-$2,460	-$42	-$487	-$2,911	-$22	-$721
$50 @ 1%						
Due to equity	$1,253	-$21	$751	$436	-$4	$314
Due to efficiency	-$5,780	-$243	-$1,840	-$5,780	-$243	-$1,840
Total	-$4,527	-$264	-$1,089	-$5,344	-$247	-$1,526
$25 @ 5%						
Due to equity	$1,445	-$17	$811	$496	-$1	$331
Due to efficiency	-$6,780	-$257	-$2,206	-$6,780	-$257	-$2,206
Total	-$5,335	-$274	-$1,395	-$6,284	-$258	-$1,875
Indices of progressivity						
Absolute	Progressive	Regressive	Progressive	Progressive	Regressive	Progressive
Relative	Regressive	Regressive	Progressive	Regressive	Regressive	Progressive
$50 @ 5%						
Due to equity	$2,413	$53	$1,420	$821	$21	$568
Due to efficiency	-$11,551	-$1,017	-$4,257	-$11,551	-$1,017	-$4,257
Total	-$9,137	-$963	-$2,837	-$10,729	-$996	-$3,689
2025 & 2050 Targets						
Due to equity	$4,521	$522	$2,755	$1,483	$156	$1,013
Due to efficiency	-$22,929	-$4,606	-$10,865	-$22,929	-$4,606	-$10,865
Total	-$18,408	-$4,084	-$8,110	-$21,446	-$4,451	-$9,851
Indices of progressivity						
Absolute	Progressive	Progressive	Progressive	Progressive	Progressive	Progressive
Relative	Regressive	Regressive	Progressive	Regressive	Regressive	Progressive

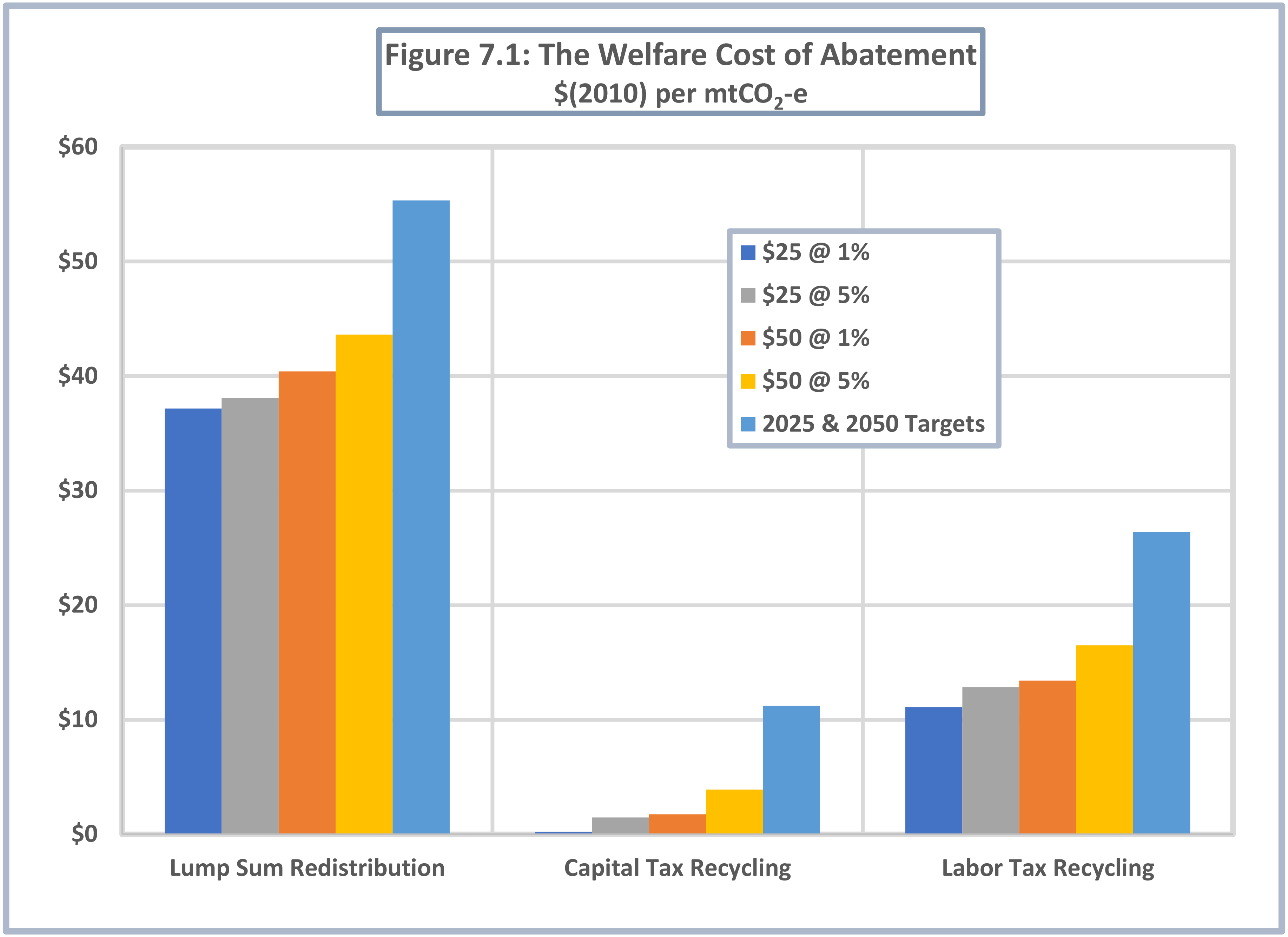

Figure 7.1: The Welfare Cost of Abatement
$(2010) per mtCO$_2$-e

Table 8.1
Comparing impacts using demand-side versus supply-side emissions modeling ($25 @ 5% case)

	Demand-side modeling		Supply-side modeling	
	Capital tax	Labor tax	Capital tax	Labor tax
Cumulative abatement ($GtCO_2$, 2015-2050)	40.7	40.4	21.8	22.0
Egalitarian welfare change, $(2010) Billions				
Total	-274	-1395	2134	798
Due to equity	-17	811	-444	528
Average percent change from base, 2015-2050				
GDP	0.20	-0.06	0.46	0.05
Consumption	-0.46	0.32	0.14	1.01
Investment	1.32	-0.78	2.22	-0.48
Exports	-0.22	-1.38	-1.01	-2.52
Imports	-0.65	-1.15	0.88	0.21
Gas mining	-9.36	-9.19	-7.93	-7.75
Coal mining	-22.15	-23.26	-22.56	-23.80
Electric utilities	-7.16	-6.64	-4.21	-3.59
Gas utilities	-7.97	-7.86	-9.07	-9.01
Petroleum refining	-6.49	-6.10	-5.06	-4.60
Primary metals	-1.29	-2.76	-5.13	-7.01
Chemicals, rubber and plastics	-0.36	-0.73	-0.74	-1.31
Transportation and warehousing	-3.37	-3.33	-1.29	-1.28