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What Are the Costs of Meeting Distributional Objectives in Designing Domestic Climate Policy?

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Abstract

This paper develops an analytical model to quantify the costs and distributional effects of various fiscal options for allocating the (large) rents created under prospective cap-and-trade programs to reduce domestic, energy-related carbon dioxide (CO_2) emissions. The trade-off between cost-effectiveness and distribution is striking.

The welfare costs of different policies, accounting for linkages with the broader fiscal system, range from –\$6 billion per year to \$53 billion per year in 2020, or between –\$12 to almost \$100 per ton of CO_2 reductions. The least costly policy involves auctioning all allowances with revenues used to cut proportional income taxes, while the most costly policies involve recycling revenues in lump-sum dividends or grandfathering emissions allowances. The least costly policy is regressive, however, while the dividend policy is progressive, and grandfathering permits is both costly and regressive. A distribution-neutral policy costs \$18–\$42 per ton of CO_2 reductions.

Key Words: cap-and-trade, welfare cost, distributional incidence, revenue recycling

JEL Classification Numbers: Q48, Q54, Q58, H22

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1. Introduction

One of the most important issues in the design of domestic, market-based climate policy is what to do with the rents or revenues created under a cap-and-trade or tax system.[1] How these policy rents are allocated and used critically affects not only the distributional impacts of the policy, but also its overall cost-effectiveness.

There are many ways to allocate policy rents. One is to give away allocations in a cap-and-trade system to existing sources, typically based on their historical emissions rates. The main motivation for this approach, called grandfathering, is political: providing compensation for producers affected by the regulation may make it easier to move legislation forward. Almost all the allowances were given away in the U.S. program to cap SO_2 emissions from power plants and, similarly, in the initial phases of the European Union's carbon dioxide (CO_2) trading program. However, more recent European and U.S. federal climate initiatives have moved away from full grandfathering because this approach substantially overcompensates emitters for their compliance costs.[2]

More recently, the United States has been concerned with distributional effects on households, particularly focusing on insulating low-income households from the prospective increase in energy prices from climate policy. Some

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[1] Other key issues include the overall stringency of the policy, its sectoral coverage (including provisions for emissions offsets), whether cap-and-trade should include price stabilization mechanisms, and to what extent supplementary instruments are warranted to address other possible market failures (e.g., technology spillovers). For a general discussion of these issues see, for example, Aldy et al. forthcoming.

[2] Power companies in the European Union earned large windfall profits when the CO_2 cap was first introduced (e.g., Sijm et al. 2006). At least for a moderately scaled CO_2 permit system, only about 15–20 percent of allowances are needed to compensate energy-intensive industries for their loss of producer surplus, so the huge bulk of the allowances could still be auctioned (e.g., Bovenberg and Goulder 2001; Smith et al. 2002).

proposals involve granting free allowances to local distribution companies with the expectation that the value of these allowances will be rebated to households in the form of lower electricity bills. Another approach that has recently gained traction is known as “cap-and-dividend,” which involves a cap-and-trade program with full allowance auctions and all the revenue returned in equal lump-sum transfers for all individuals. An argument for this approach is that all individuals have equal ownership rights to the environment, and therefore proceeds from charging for use of the environment should be shared equally.

A key drawback of both approaches is that they forgo the potentially large efficiency gains from using allowance auction revenues to cut other distortionary taxes. Personal income and other taxes distort capital and labor markets by depressing net factor returns. They also distort household consumption decisions by allowing exemptions or deductions for particular types of spending (e.g., employer medical insurance). Therefore, using revenues to lower the rates of these distortionary taxes produces gains in economic efficiency that can substantially lower the overall welfare costs of climate policy (though this approach may do little to help with distributional objectives). In fact, without this counteracting revenue-recycling effect, the welfare costs of market-based climate policies are substantially higher in the presence of distortionary taxes. The distortions raise production costs and product prices, thereby lowering real factor returns and factor supply (e.g., Goulder et al. 1999; Fullerton and Metcalf 2001).

To date, no climate bills have been introduced in the U.S. Congress that would use policy revenues to reduce marginal income tax rates, though some include uses that would have similar effects.[3] Moreover, considering this case helps clarify the quite striking trade-offs involved in allocating climate policy rents.

In this paper, we develop and parameterize an analytical general-equilibrium model that synthesizes two different strands in the literature on domestic climate policy. One focuses on the cost-effectiveness of alternative market-based policies in a homogeneous agent framework, and the other looks at distributional effects in multi-agent models but with no attention to efficiency.

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[3] The Waxman–Markey bill (H.R. 2454), for example, devotes a portion of revenue to deficit reduction. If that deficit reduction otherwise would have been accomplished by raising marginal rates, this would have the same effect as lowering marginal rates. In addition, H.R. 1337, a bill sponsored by Representative John Larson (D-CT), would have used revenues to exempt a portion of income from payroll taxes. While this form of recycling would increase the return to labor force participation, it would be less efficient than cutting marginal income tax rates. The latter would also increase effort on the job and reduce the bias toward tax-preferred spending. CO_2 taxes, which are largely revenue neutral, have been implemented in British Columbia and in Scandinavian countries, though a tax proposal for France (with very limited coverage) was recently ruled unconstitutional.

While some of our results—such as the low cost-effectiveness of cap-and-dividend and grandfathered permits—have been recognized for some time, our analysis offers a more complete picture of efficiency/distributional trade-offs than can be gleaned from prior literature.[4]

Our analysis considers three bounding cases for rent allocation and use under cap-and-trade systems. These include full grandfathering of allowances, full auction of allowances with revenues returned to households in lump-sum dividends, and full auctions with revenues recycled in equal, proportionate cuts in marginal income taxes across all household groups. We also consider a “distribution-neutral” policy, where the tax and benefit system is adjusted to neutralize any distributional effects of the cap-and-trade policy on households, leaving the overall policy change neither progressive nor regressive. Policymakers are more likely to choose combinations of our bounding cases, rather than using 100 percent of rents for one purpose alone; however, the implications of these combinations are easily inferred by taking the appropriate weighted averages of our bounding cases. Furthermore, although our discussion is couched in terms of cap-and-trade, each cap-and-trade variant has an emissions tax counterpart in our analysis.[5]

New revenue sources might be used in many ways other than those we study. These run the gamut from program-enhancing measures like clean technology programs, incentives for energy efficiency, and capacity investments to facilitate adaptation to climate change, to general increases in public spending and federal deficit reduction. However, it is difficult to make general statements

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[4] Prior analyses by Burtraw et al. (2009), Dinan and Rogers (2002), and Parry (2004) have studied the distributional impacts of various options for recycling climate policy revenues through the tax system. Many other papers have been written on how linkages between environmental policies and the broader tax system affect the overall costs of policy (see, for example, Goulder et al. 1999; Fullerton and Metcalf 2001; Bovenberg and Goulder 2002; Schöb 2006).

Our analysis is more than just the sum of findings from these two literatures, however. Most importantly, the efficiency and distributional results come from the same model and thus are directly comparable. This model has several additional advantages. Unlike in most prior literature, we account for broader distortions of the tax system beyond those in factor markets, so we can integrate empirical findings from recent public finance literature on the taxable-income elasticity. Furthermore, our distributional analysis takes into account implicit burdens on households from the changes in deadweight loss from the broader fiscal system. Moreover, we account for indexing the tax/benefit system to inflation, which provides some (limited) automatic adjustment to higher energy prices. In addition, our type of multi-agent model is needed to avoid aggregation bias when households face different tax rates, benefit differently from revenue-recycling schemes, and have different behavioral responses to tax changes. Finally, the distribution-neutral approach we use has not been analyzed previously in the context of carbon policy.

[5] For example, a carbon tax with revenues returned in lump-sum transfers to firms proportionate to their historical emissions would be equivalent to cap-and-trade with grandfathered allowances. The tax and cap-and-trade approaches would differ if our analysis were extended to incorporate uncertainty over future emissions abatement costs (e.g., Pizer 2003).

about the potential efficiency implications from these broader alternatives for revenue use without specific evidence on the benefit and costs of the spending measures, accounting for possible market failures that they might address. Even the effects of deficit reduction are opaque, as it is unclear whether lower debt burdens for future generations will lead to lower taxes or more public spending.

We find that the allocation of rents under cap-and-trade or use of revenues under carbon taxes can have huge efficiency and distributional consequences for carbon policy. These effects can be much larger than the direct effects of the carbon policy itself.

Within the range of options we consider, the direct cost of reducing CO_2 emissions to 9 percent below business-as-usual levels in the year 2020 is $9 billion.[6] However, the overall welfare costs of different policies, accounting for linkages with the broader fiscal system, range from *negative* $6 billion per year to $53 billion per year. In terms of average cost of CO_2 reductions, this range is huge—from –$12 to almost $100 per ton.

The distribution of that cost ranges from highly progressive (with the bottom two income quintiles bearing a negative burden) to highly regressive (with the top two quintiles bearing a negative burden). There are stark trade-offs between cost-effectiveness and distribution in the design of market-based climate control policies. A cap-and-dividend approach makes carbon policy more progressive at the expense of dramatically raising the overall cost, and conversely, using revenue to fund a proportional income tax cut lowers overall cost but leads to a regressive distribution of those costs. A distribution-neutralizing tax change represents a middle ground for both efficiency and distributional effects. Cap-and-trade with grandfathered allowances performs poorly on both cost and distributional grounds, though it may reduce industry opposition and thus be more politically feasible.

The rest of the paper is organized as follows: Section 2 develops our analytical framework and key formulas for the efficiency cost and distributional burden of different policies. Section 3 describes the model parameterization. Section 4 presents the main quantitative findings and sensitivity analysis. Section 5 offers concluding remarks.

2. Analytical Framework

A. Model Assumptions

We use a long-run, comparative static model with multiple agents, each representing an average over all households within a particular income class.

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[6] All figures are in year 2007 $.

Households choose consumption of general goods, products that are energy intensive, products that receive favorable treatment from the tax system, and labor supply. The government prices CO_2 emissions through a cap-and-trade system, which in turn drives up energy costs and product prices in general. Rents created by climate policy may accrue to the private sector (e.g., through free allowance allocation) or to the government. In the latter case, revenues are used to adjust the income tax-and-transfer system.

(i) Household utility. We divide households into five equal-sized income groups, indexed by *i*, where $i = 1$ and $i = 5$ denote the lowest and highest income quintiles, respectively. Each group is modeled as a single representative household, with the utility function:

$$u_i(X_{iE}, X_{iF}, X_{iC}, L_i, G^{PUB}) . \tag{1}$$

X_{iE} denotes consumption of an aggregate of goods whose production or use is energy intensive (e.g., electricity-using durables, auto travel, home heating fuels). X_{iF} is consumption of goods that are favored through the broader tax system, such as employer-provided medical insurance or owner-occupied housing. X_{iC} is an aggregate of all other (non–energy intensive, non–tax favored) goods. L_i is work effort, implicitly combining labor force participation rates and average hours worked on the job by households in that group. G^{PUB} is government spending on public goods, which is fixed and included only to scale income tax rates to their observed levels. u_i is quasi-concave, twice differentiable, decreasing in labor supply, and increasing in all other arguments.

(ii) Household budget constraint. The household budget constraint is given by:

$$\sum_j p_j X_{ij} = I_i , \tag{2}$$

where $j = E, F, C$ indexes the three goods and p_j is the market price of good *j*.

The tax-and-transfer system, reflecting state and federal personal income taxes, employer and employee payroll taxes, and sales taxes, minus government transfers, is represented as a piecewise-linear function with five segments for each of the five income groups. For simplicity, we assume that any policy-induced change in taxable income will be sufficiently small that no group will move to a different segment of the tax schedule. Under this assumption, the tax schedule group *i* faces is equivalent to a linear tax with rate t_i and intercept $-G_i$ (which can be found by extending the relevant segment of the piecewise-linear tax schedule to a point with zero pre-tax income). Disposable income (I_i) consists of taxable income (Γ_i), net of taxes paid on that income. This gives

$$I_i = (1 - t_i)\Gamma_i + G_i . \tag{3a}$$

Taxable income consists of the wage w_i times labor supply, plus lump-sum net-of-tax profit income π_i, less spending on tax-favored goods. Profit income accrues to households via their ownership of firms and reflects any producer rents created by cap-and-trade policy.

(3b) $\Gamma_i = w_i L_i + \pi_i - p_F X_{iF}$.

The (pre-existing) tax system causes two sources of distortion. First, it distorts labor supply by depressing the returns to work effort. Second, it creates a bias toward tax-preferred spending. The combined effect of carbon policies on these two distortions can be summarized by changes in taxable income.[7]

(iii) Production, CO_2 emissions, prices, and rents. All goods are produced under constant returns to scale under perfect competition (hence there are no pure profits in the absence of carbon policy). Market prices of goods, which implicitly incorporate any energy costs associated with their use, are determined by:

(4) $p_j = \rho_j p_H + \beta_j$.

Here ρ_j is the energy intensity of good j, where $\rho_E > \rho_C, \rho_F$, p_H is the price of energy, and β_j is a parameter representing non-energy costs.[8]

The price of energy is determined as follows:

(5) $p_H = c(z^0 - z) + \tau z + p_H^0$,

where z is CO_2 emissions per unit of energy; $c(.)$ is a positive, convex abatement cost function ($c(0) = 0$); and a superscript 0 denotes the initial value of a variable (prior to the introduction of carbon policy). A reduction in z represents a switch to lower-carbon but more expensive fuels in energy production (e.g., a switch from coal to renewables or nuclear power). Emissions are priced at rate τ, which reflects the allowance price. Our assumptions also imply that emissions prices and abatement costs will be fully passed through into energy prices. As discussed below, this assumption is debatable, although it does not affect the key focus of our paper, which is the trade-off between costs and distributional goals in allowance allocation.

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[7] We implicitly assume that tax preferences do not address any market failures and thus are purely distortionary.

[8] For simplicity, ρ_j is taken as fixed though relaxing it would not affect the results, given our parameterization below.

Economy-wide CO_2 emissions, Z, are the product of the emissions intensity of energy and energy use aggregated over all products and households:

(6) $$Z = z\sum_j \rho_j \sum_i X_{ij} \ .$$

For simplicity, we focus on a policy covering CO_2 only, which accounts for about 80 percent of total U.S. greenhouse gases. In addition, the (energy-related domestic) CO_2 reductions and the emissions price are approximately consistent with those projected under recent climate legislation.[9]

Profit income to household group i is given by:

(7) $$\pi_i = \theta_i \phi \tau Z \ .$$

θ_i is the fraction of (economy-wide) energy capital owned by household group i, where $\Sigma_i \theta_i = 1$ and θ_i is larger for higher-income groups. Implicitly, this energy capital includes both retirement and non-retirement bond and stockholdings. ϕ is the portion of policy rents that are left in the private sector, as opposed to accruing to the government in revenue. $\phi = 0$ represents a cap-and-trade system with full allowance auctions. $\phi = 1$ represents a system with 100 percent free allowance allocation to energy firms, where entire policy rents τZ are reflected in higher firm equity values as well as stockholder wealth and such income is not taxed. Intermediate cases might represent partial taxation of allowance rents or partial auctioning of allowances. Outcomes for these cases are easily inferred by taking weighted averages of the results below.

(iv) Government constraints and policy. The government is subject to the budget constraint

(8) $$G^{PUB} = \sum_i t_i \cdot \Gamma_i - \sum_i G_i + (1-\phi)\tau Z \ .$$

This constraint requires that spending on public goods equals revenue from the income tax system, plus revenue from the carbon policy.

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[9] Although current legislation allows firms to purchase offsets in other domestic sectors (e.g., forestry and agriculture) and countries, we do not count these offsets as part of the emissions reduction. We also exclude the deadweight losses (in other sectors or countries) associated with these broader reductions. A key concern with offsets is the difficulty of verifying whether these broader emissions reductions would have occurred anyway and whether they might be negated through increased emissions elsewhere. For example, slowed deforestation in one country might accelerate deforestation in other countries through a rise in global timber prices.

Following the introduction of a carbon policy, the intercept terms in the tax schedule are adjusted as follows:

$$(9) \qquad G_i = G_i^0 \overline{p} + \hat{G}_i , \qquad \overline{p} = \sum_j \mu_j p_j , \quad \mu_j = \frac{\sum_i X_{ij}^0}{\sum_{ij} X_{ij}^0}$$

where we have normalized all initial product prices to unity. $\overline{p}$ is the general price level, a weighted average of market prices where the weight μ_j is the (initial) share of economy-wide spending (or consumption) on good j.

According to (9), the nominal tax schedule is automatically indexed to inflation to reflect increases in the general price level, implying that marginal and average tax rates depend on real income. In addition, some schemes devote a portion of the new revenues to making the policy more progressive, which implies an additional adjustment $\hat{G}_i$ to transfer payments.

More specifically, we consider four bounding cases for the allocation and use of policy rents (each defined for the same emissions reduction and price):

Proportional income tax cut ($\phi = 0 , \hat{G}_i = 0$). In this case, all policy rents go to the government, and after indexing the nominal tax schedule, all other revenue is used to finance an equal reduction in the marginal tax rate all income groups face, i.e., $dt_i / d\tau = dt / d\tau < 0, \forall i$.

Cap-and-dividend ($\phi = 0 , \hat{G}_i = \hat{G} > 0$). For this policy, allowances under a cap-and-trade policy are fully auctioned, with revenues (after indexing) returned in equal lump-sum transfers to households.

Grandfathered permits ($\phi = 1 , \hat{G}_i = 0$). All allowances are given away for free, and all policy rents accrue to households through their ownership of firms. Again, we abstract from taxation of rents.

Distribution-neutralizing tax cut ($\phi = 0 , \hat{G}_i \neq 0$). Whereas the tax change in the proportional tax cut case entails the same change to all marginal tax rates, the distribution-neutral case requires changing marginal income tax rates by different amounts at different points in the income distribution to equalize the net burden as a percentage of income across all quintiles.[10] The efficiency gains from revenue

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[10] This is similar to the approach of Williams (2009a and 2009b) and Kaplow (2004) when considering a distribution-neutralizing tax change in other policy contexts. However, while those papers assume a continuous income distribution, this paper works with a discrete distribution made up of five quintiles.

recycling are smaller in the distribution-neutral case than in the case with proportional tax rate reductions because marginal rates fall by less in this case than in the proportional tax cut case. Cutting tax rates on low-income groups leads to a relatively large drop in tax revenue because all higher-income groups also benefit from the rate reductions for the lower-income brackets. Consequently, a tax cut disproportionately targeted at lower-income groups will yield a smaller reduction in marginal rates than would a proportional tax cut.

In all four cases, we assume that equal, proportionate adjustments to all marginal income tax rates make up any indirect revenue losses.[11] These losses stem from reductions in taxable income as households, for example, reduce labor supply in response to lower real wages as higher energy prices drive up the general price level.

One noteworthy limitation of our analysis is that the model does not capture distortions from taxes on capital income. In this regard, we mischaracterize, though perhaps only moderately, the efficiency gains from, and the incidence of, proportional cuts in marginal income taxes. More generally, incorporating taxes on capital income would admit a wider range of possibilities for changes in the taxation of personal and corporate income in response to recycling revenue from allowance sales.

B. Formulas for Efficiency Costs and Distributional Burdens of Carbon Policies

The main formulas of interest in this paper are general expressions for the components of the efficiency costs and distributional burdens of carbon policies. They also express how those components vary under the allocation and recycling options just described. The formulas below are (reasonable) approximations given the scale of emissions reductions considered and would be exact if demand and marginal abatement cost curves were linear over the relevant range. Derivations for the formulas are provided in the appendix.

(i) Efficiency costs. The (approximate) efficiency cost of a carbon policy that reduces aggregate CO_2 emissions by an amount $\Delta Z = Z^0 - Z$, with associated emissions price τ, can be decomposed into the following four components:

$$(10a) \quad WC^{HT} - WG^{RR} + WC^{TI} + WC^{INC}$$

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[11] Alternatively, we could assume that indirect revenue losses are deducted from the amount of revenue returned in transfers under cap-and-trade, or the size of the allowance giveaway under grandfathered permits, with significant implications for distributional incidence. However, our assumption reflects actual policy proposals (especially given the difficulty of accurately projecting indirect revenue losses).

$$WC^{HT} = \frac{1}{2}\cdot\tau\cdot\Delta Z \ , \qquad WG^{RR} = MEB\cdot\left\{(1-\phi)\tau E - \sum_i \Delta G_i\right\},$$

$$WC^{TI} = (1+MEB)\cdot\sum_i t_i\frac{\partial\Gamma_i}{\partial\overline{p}}\Delta\overline{p} = (1+MEB)\cdot\sum_i \alpha_i^I t_i \varepsilon_i^{\overline{p}}\tau\left(Z+\frac{\Delta Z}{2}\right),$$

$$WC^{INC} = -(1+MEB)\cdot\sum_i t_i\frac{\partial\Gamma_i}{\partial G_i}(\Delta G_i+\pi_i) = -(1+MEB)\cdot\sum_i \alpha_i^I t_i \varepsilon_i^I\frac{\Gamma_i}{I_i}\Delta G_i \ ,$$

where

(10b) $$MEB = \frac{-\sum_i t_i\dfrac{\partial\Gamma_i}{\partial t_i}}{\sum_i \Gamma_i + \sum_i t_i\dfrac{\partial\Gamma_i}{\partial t_i}} = \frac{\sum_i \alpha_i^\Gamma \varepsilon_i^t \dfrac{t_i}{1-t_i}}{1-\sum_i \alpha_i^\Gamma \varepsilon_i^t\dfrac{t_i}{1-t_i}} \ ,$$

$$\varepsilon_i^t = \frac{\partial\Gamma_i}{\partial(1-t_i)}\frac{1-t_i}{\Gamma_i}, \qquad \varepsilon_i^{\overline{p}} = \frac{\partial\Gamma_i}{\partial\overline{p}}\frac{\overline{p}}{\Gamma_i}, \quad \varepsilon_i^I = \frac{\partial\Gamma_i}{\partial I_i}\frac{I_i}{\Gamma_i}, \quad \alpha_i^\Gamma = \frac{\Gamma_i}{\sum_i \Gamma_i} \ ,$$

$$\alpha_i^I = \frac{\Gamma_i}{\sum_i I_i} \ .$$

Beginning with (10b), ε_i^t, $\varepsilon_i^{\overline{p}}$, and ε_i^I denote three different taxable income elasticities for household *i* defined with respect to changes in marginal tax rates, changes in the general price level, and changes in (taxable) household income, respectively. α_i^Γ is the share of household group *i*'s taxable income in economy-wide income.

MEB is the marginal excess burden of taxation, the efficiency cost of raising an extra dollar of revenue through a proportionate increase in marginal income taxes. The numerator of *MEB* is the efficiency loss from an incremental increase in the marginal income tax for group *i*, aggregated over all households. The efficiency loss for group *i* is the induced reduction in taxable income (reflecting both reductions in labor supply and increases in tax-preferred spending) times the marginal tax rate. The denominator of the *MEB* is the extra revenue from the tax increase, summed over all households. Alternatively, the *MEB* can be expressed as a function of the weighted sum of taxable income elasticities (with respect to tax rates) for different household groups, with weights equal to the households' share in economy-wide taxable income. Note that according to the way we have defined it in (10b), behavioral responses underlying the *MEB* are uncompensated.

In equation (10a), the first component of the welfare cost, WC^{HT}, corresponds to the Harberger triangle under the economy-wide marginal abatement cost curve. This curve represents the envelope of other marginal abatement cost curves for each margin of behavior for reducing emissions—reducing emissions per unit of, and reducing overall consumption of, energy-intensive products.[12] The Harberger triangle is the same under all four policy scenarios.

The second component in (10a), WG^{RR}, termed the revenue-recycling effect (e.g., Goulder 1995), is the efficiency gain that results to the extent that revenues are used to reduce marginal income taxes. This component is the product of the *MEB* and the amount of revenue recycled in this fashion, or the policy rents retained by the government less what is spent on transfer payments and indexing.

The third welfare cost component, WC^{TI}, is the tax-interaction effect. Most prior work refers to this component as the welfare loss from the reduction in labor supply as policy-induced increases in the general price level reduce the real return to work effort (e.g., Goulder 1995). The welfare loss in this earlier work is the change in labor earnings, multiplied by the labor tax distortion, and multiplied by 1+*MEB*, as higher (distortionary) taxes must make up lost labor tax revenues to maintain budget balance. In these models, the change in labor earnings depends on the responsiveness of labor supply to higher prices and the loss of worker surplus from the price increase. The latter is (approximately) equal to allowance rent plus the Harberger triangle under the marginal abatement cost curve and corresponds to $\tau(Z + \Delta Z / 2)$ in our formula for WC^{TI}. However, we measure the tax-interaction effect with respect to changes in taxable income and response to higher product prices rather than labor earnings; hence the taxable-income elasticity appears in our formula, rather than labor-supply elasticity. The tax-interaction effect as we define it is also constant across different policies.

Our expression for WC^{TI} embeds a number of simplifying assumptions that might, to some degree, be open to question (see the appendix). One is that we assume all goods are equal substitutes for leisure and therefore not deserving of any Ramsey tax or subsidy from an optimal tax perspective. In the absence of evidence to the contrary, however, this seems a reasonable, neutral assumption. Another simplification is that compliance costs are fully passed forward into higher prices. To the extent that compliance costs come at the expense of infra-marginal rent earned on baseload power generation, for example, the price effect

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[12] These marginal cost curves all come out of the origin, given that our model abstracts from other distortions, such as fuel taxes, automobile congestion, and non-competitive pricing of electricity, that affect the production and use of energy.

and tax-interaction effect will be weaker.[13] In short, the reader should bear in mind that the absolute value of the tax-interaction effect is difficult to pin down accurately, though this is not relevant for the cost/distributional tradeoffs involved in allocating cap-and-trade rents, which is the main focus of our paper.

The final component of welfare cost, WC^{INC}, reflects efficiency losses from the reduction in taxable income in response to higher lump-sum income—through higher government transfers and/or profit income. This largely reflects a reduction in labor supply as households take more leisure, which is a normal good.

(ii) Distributional burden. The distributional burden of the emissions-pricing policy on household group *i*, relative to income, is fairly straightforward and can be approximated by the following equation (see the appendix for derivations):

$$(11) \qquad \sum_j \frac{\Delta p_j^0 X_{ij}^0}{I_i^0} + \frac{\Delta G_i + \pi_i}{I_i^0} + \frac{\Delta t_i \Gamma_i}{I_i^0}.$$

The first term reflects the (first-order) consumer surplus loss from the induced increase in energy prices. The second term picks up possible benefits from dividends and rent income through stock ownership under grandfathered permits. The third term reflects gains from reductions in marginal tax rates. The distribution analysis includes the efficiency consequences from the revenue-recycling, tax-interaction, and income effect on labor supply through overall changes in marginal income tax rates in the third term. We omit the Harberger triangle from the distributional analysis because it is small relative to the first-order loss of surplus to households from higher energy prices.

3. Parameterization of the Model

Our baseline parameter assumptions are summarized in Table 1. We focus on projections for year 2020. All monetary figures are expressed in year 2008 dollars (or thereabouts).

(i) Income distribution. To obtain the income distribution, we use data from the Consumer Expenditure Survey (CEX) for years 2007 and 2008, for households that completed their year in the survey panel during 2008.[14] As is standard in

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[13] The price pass-through may also be imperfect in states that retain cost-of-service regulation for power generation. In this case, utilities receiving free allowance allocations cannot pass forward the opportunity cost of such allowances in higher generation prices. See Parry 2005 for more discussion of these issues.

[14] The CEX uses a rotating panel design: each calendar quarter, one-fourth of the households in the sample are rotated out, so each household appears in the data for four quarters. Obtaining a full year of data on each household that completed its time in the panel during 2008 therefore requires using data from both 2007 and 2008.

incidence analysis, we divide households into quintiles in two different ways: by their pre-tax annual income and their total consumption.[15] To the extent that households are able to smooth consumption over time, the consumption-based measure will more accurately reflect lifetime income. Distributional differences are more muted when measured based on consumption quintiles than when measured based on income quintiles.

Under either measure, quintile 1 is the lowest 20 percent of income earners, quintile 2 the next lowest 20 percent, and so on. For simplicity, we assume the real income and real consumption of each household group grows at the same 1.5 percent annual rate out to 2020. In 2020, income per household varies from $11,307 for the lowest income quintile to $181,626 for the top quintile, and consumption varies from $19,253 for the lowest consumption quintile to $126,173 for the highest (Table 1).

(ii) Budget shares for energy-intensive goods. In the analytical model, goods are either energy intensive or non–energy intensive. In the real world and in the data, goods vary widely in their energy (and thus carbon) intensity. One could simply divide goods into energy-intensive and non–energy intensive categories and assign all energy-intensive goods the same embodied carbon content and all non–energy intensive goods a lower- or zero-embodied carbon content. But given the wide variation in embodied carbon across goods, this could introduce substantial inaccuracy when measuring the distributional burden of a carbon tax.

Instead, we estimate the total carbon embodied in all the goods a household consumes and then define the consumption of energy-intensive goods in the model to be proportional to that total. In effect, this treats consuming a particular good from the CEX as consuming some of the energy-intensive good and some of the non–energy intensive good, with the relative proportions being determined by the embodied carbon content of that good. We take the estimates of embodied carbon for goods in the CEX from Hassett et al. (2007), who calculate those estimates based on input–output tables from the U.S. Bureau of Economic Analysis.

(iii) Stock ownership. We calculate stock ownership by aggregating for each quintile the value of estimated market value of all stocks, bonds, mutual funds, and other such securities each household reports in the CEX. According to this calculation, the top income quintile owned 59.8 percent of stockholdings, while

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[15] Because income in the CEX is poorly measured for low-income households, it is customary for incidence studies to drop some very low-income households to minimize the effects of that measurement problem. We follow the same approach as Grainger and Kolstad (2010), dropping households with reported income below $7,500 but not altering the quintile cutoff levels of income and expenditure as a result of dropping those households.

the lowest income quintile owned 2.6 percent. Stock ownership shares are assumed to be the same in 2020 as in 2007–2008.[16]

(iv) Household tax rates and transfers. We obtained marginal and average rates of federal and state income taxes (accounting for the earned income tax credit and child tax credits), as well as sales taxes, by running each household from the CEX data for 1997–1999 through the National Bureau of Economic Research's TAXSIM model, using the tax laws for those years and then aggregating for each quintile.[17] We add in employer and employee payroll taxes (based on statutory rates) to obtain the overall income tax rates (assumed to apply in 2020) shown in Table 1. Marginal tax rates vary from 0.17 for the bottom income quintile to 0.41 for the top income quintile and average (weighted by taxable income) 0.40.

(v) Taxable-income elasticities. During the last decade, a substantial number of papers have estimated the elasticity of taxable income with respect to tax rates, for the economy as a whole and for high-income taxpayers. Although initial estimates of this elasticity are quite large (e.g., Feldstein 1999), more recent estimates are considerably smaller, in part reflecting better data and improved methods of controlling for non-tax factors affecting changes in taxable income. Based on a careful review of evidence for the United States and other countries, Saez et al. (2009) put the taxable-income elasticity (for the economy as a whole) at 0.12 to 0.40, with more estimates closer to the top of this range than the bottom.[18]

Although we assume that all taxpayers have the same labor-supply elasticity, higher-income taxpayers tend to have more scope for exploiting tax preferences, so they tend to have higher taxable-income elasticities. We assume taxable-income elasticities with respect to tax rates vary between 0.2 for the bottom income quintile and 0.35 for the top income quintile, as shown in Table 1,

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[16] Ideally, we would use information on the pattern of stock ownership across energy-intensive firms (rather than all firms) to gauge the distribution of rent income under grandfathered permits. However, this information is difficult to obtain because most stocks are owned indirectly through large investment firms.

[17] These years predate the federal income tax cuts of 2001 and 2003, and thus will approximate the taxes that will apply if those tax cuts are allowed to expire (which seems increasingly likely over time, given budgetary pressures). We feel this provides a better approximation to the tax laws in 2020 than would using the 2008 tax laws. To the extent that this over- or underestimates marginal tax rates in 2020, the magnitudes of the revenue-recycling and tax-interaction effects will also be over- or underestimated.

[18] One caveat is our representation of the taxable-income elasticity is slightly mismatched with empirical estimates of that elasticity. In our model, this elasticity reflects tax-induced reductions in labor supply and shifting to tax-preferred consumption, whereas empirical studies summarize a broader range of responses, including shifting to tax-sheltered saving. This mismatch (which we believe is not too important for our purposes) is due to our characterizing the income tax system as a tax on labor alone, rather than a tax on both labor and capital income.

where (weighting by household shares in taxable income) the average elasticity is 0.31.

An increase in the general price level (in response to carbon policy) has a comparable effect on labor supply to a reduction in the real household wage—that is, households substitute leisure for work, though an income effect in the opposite direction partly offsets this outcome. The effect on tax-preferred spending should be small because the price of ordinary spending does not change relative to the price of tax-favored spending.[19] For the same reason, the change in taxable income in response to higher lump-sum payments should be similar to the change in labor earnings. We therefore use standard values for the uncompensated labor-supply elasticity, and income elasticity of labor supply, namely 0.15 and -0.2 (e.g., Blundell and MaCurdy 1999), as proxies for $\varepsilon_i^{\bar{p}}$ and ε_i^I for all households.

(vi) Emissions reductions and prices. These are based on a policy simulation of representative climate bills reported in Krupnick et al. (2010) using a variant of the Energy Information Administration's National Energy Modeling System (NEMS). NEMS is a dynamic, economic–engineering model of the economy, with considerable detail on a wide spectrum of existing and emerging technologies across the energy system. A large number of modeling groups use its projections.

Without climate policy, this model projects CO_2 emissions to be about 6 billion metric tons in 2020. The electricity and transport sectors account for about 40 and 33 percent of these emissions, respectively, and other sources (i.e., non-electricity emissions from the industrial, commercial, and residential sectors) account for the remaining 27 percent. A climate policy that prices CO_2 allowances at $33 per ton in current dollars reduces energy-related CO_2 emissions by about 9 percent below business-as-usual levels in 2020, or by 0.54 billion tons (Krupnick et al. 2010).[20] Thus, the Harberger triangle, WC^{HT}, is about $9 billion, and policy rents, τZ, are about $180 billion. The carbon policy increases energy prices in our model by 7.9 percent or the general price level by 0.5 percent.

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[19] Although tax-preferred spending will fall in response to higher energy prices, the resulting efficiency gain (due to offsetting the tax subsidy) is modest relative to the efficiency loss from the reduction in labor supply. This is because the "market" for tax-preferred spending is small (about 10–15 percent) relative to the labor market.

[20] This policy run involves a more aggressive emissions reduction target but allows domestic and international offsets (under an intermediate assumption about the availability of such offsets). Here, we assume that the same emissions price projected by this run is imposed but is applied only to CO_2 with no offsets. In either case, the reduction in domestic, energy-related CO_2 should be essentially the same.

4. Results

A. Cost Comparison

Figure 1 shows the overall cost of imposing a carbon policy with an allowance price of $33 per ton of CO_2, under each of the four options for the use of allowance rents: a proportional income tax cut, lump-sum rebates to households under a cap-and-dividend system, free allocation of permits to firms based on grandfathering, and a distribution-neutralizing tax cut. For this last option, the cost varies substantially based on whether the tax cut neutralizes distributional effects across income quintiles or across consumption quintiles, so these are presented separately. Note that Figure 1 provides just an estimate of policy costs; it does not incorporate any estimates of the climate benefits from lower CO_2 emissions.

For each case, the figure also shows the four components of welfare cost: the Harberger triangle term (the partial-equilibrium cost, ignoring any interactions with the tax system); the revenue-recycling effect (the gain from using allowance rents to finance tax rate cuts); the tax-interaction effect (the general-equilibrium loss resulting when higher energy prices discourage labor supply); and the income effect on labor supply (a further general-equilibrium loss as the income effect from the distribution of policy rents further discourages labor supply). The Harberger triangle is the same across all the policy simulations ($8.9 billion a year in 2020), as is the tax-interaction effect ($25.0 billion). However, the revenue-recycling effect, in particular, differs across policies, as does the income effect on labor supply.

When allowance rents are used to finance a proportional income tax cut, the overall cost of the policy is –$6.4 billion per year. This case yields a “strong” double dividend (Goulder 1995): even ignoring the benefits of reduced carbon emissions, the cost of the policy is still negative. As discussed in Parry and Bento (2000), when certain categories of spending are tax favored, the gains from the revenue-recycling effect are magnified relative to a case without such tax preferences, but the losses from the tax-interaction effect are approximately unaffected. As a result, the revenue-recycling effect (a gain of $41.3 billion) exceeds the tax-interaction effect by enough to more than offset the Harberger triangle. This qualitative result is different than in earlier literature that focused only on the labor market distortion caused by the tax system (e.g., Goulder 1995). In the latter models, the revenue-recycling effect typically falls short of the tax-interaction effect, and the overall cost of auctioned cap-and-trade systems (or carbon taxes) is positive, exceeding the Harberger triangle.[21]

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[21] Similarly, if tax preferences were entirely justified by market failures, the revenue-recycling effect would be smaller. In this case, the overall cost of our proportional tax cut case would be positive (roughly $15 billion).

The welfare cost of the cap-and-trade policy is highest under either the cap-and-dividend or free permit allocation cases: under each of these options the cost is roughly $50 billion a year in 2020. By giving away the permit rents, these two options give up the large gain from the revenue-recycling effect ($41.3 billion). In addition, they produce a smaller, yet significant loss of $6.4 billion (under cap-and-dividend) or $11.6 billion per year (under grandfathered permits) because the resulting lump-sum income to households reduces labor supply. This effect is stronger for the grandfathered permit case because higher-income households—who face higher marginal income tax rates—receive a disproportionately larger share of the policy rents in this case. The overall welfare cost of the cap-and-dividend and grandfathered permit polices is more than five times the Harberger triangle, underscoring the bias in cost analyses that omit interactions with the broader tax system.[22] Dividing total costs by the CO_2 reduction (0.54 billion tons), the average cost per ton reduced is around $90 under cap-and-trade, compared with –$12 in the proportional tax reduction case.

Indexing taxes and transfers for inflation in the above policy cases requires revenue outlays of $30 billion per year in 2020, or one-sixth of the policy rents. The implied increase in marginal tax rates to cover this revenue loss adds $7.4 billion per year to overall welfare costs. In the proportional income tax case, this cost leads to a smaller overall gain from the revenue-recycling effect, while in the grandfathered permit and cap-and-dividend cases (which give away the entire $180 billion of policy rents), it is reflected in a negative revenue-recycling effect.[23]

The overall cost of the distribution-neutral options fall between the cost under the proportional tax cut and the cost under the cap-and-dividend policy—

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[22] These results implicitly assume that permit rents are not taxed under either policy option. This is very likely to be true in the cap-and-dividend case. However, in the free permit allocation case, the permit rents could well be taxed, at least in part. To the extent that these rents accrue to stocks held in taxable accounts (as opposed to retirement or other tax-sheltered accounts), they will be subject to tax. Under either policy option, if the rents are taxed, then the overall cost will be a linear combination of the cost under that policy option (which assumes that no rents are taxed) and the cost under the proportional tax cut (which is equivalent to a case in which all the permit rents are taxed at a rate of 100 percent).

[23] Note that because the tax system is indexed such that tax rates depend on real income, the overall results—for efficiency and distribution—do not depend on the particular normalization used for prices (i.e., the choice of numéraire). However, the decomposition of those results into indexing for inflation and other components does depend on the price normalization. We use a price normalization that holds the pre-tax wage constant, so a rise in the price of consumer goods relative to labor shows up as an increase in the overall price level, which produces the results shown here. If instead we were to use a normalization that holds the price of consumer goods constant, that same relative price change would show up as a reduction in the pre-tax wage. In this case, indexing for inflation would have no revenue cost; instead, a reduction in income tax revenue would result from the lower wages. Thus, the overall effect would be the same, but the decomposition of that effect between indexing for inflation and other effects on revenue would differ.

welfare costs are \$9.9 and \$22.6 billion in the consumption-based and annual income-based cases for measuring inequality, respectively. The distribution-neutralizing tax change lowers tax rates rather than providing a lump-sum transfer, so it generates a gain from the revenue-recycling effect, which causes the overall cost to be substantially lower than the overall cost under the cap-and-dividend and grandfathered permits. However, because the tax cuts are larger for lower-income households (to offset the regressive incidence of higher energy prices), the marginal tax rate reductions and corresponding efficiency gains from revenue recycling are smaller than in the proportional tax cut case. This effect is even more pronounced when inequality is measured using annual income rather than consumption. In the former case, higher energy prices are more regressive, requiring an even greater concentration of tax cuts among lower-income households. Thus, the revenue-recycling gains are \$15.8 billion in this case, compared with \$25.7 billion when inequality is measured using the consumption approach.

B. Distributional Effects

Figures 2 and 3 summarize the distributional burdens of the different policies across income quintiles, based on income and consumption quintiles, respectively. Burdens are expressed as a percent of household income. In addition, the net burden is decomposed into the burden of the higher energy prices caused by the cap-and-trade program; the gain to households resulting from indexing the tax-and-transfer system for inflation; any gain from reductions in marginal income tax rates; and possible gains from permit rents or lump-sum dividends.[24]

All policies impose the same pattern of burdens across households due to higher energy prices. This burden component falls with income—for example, the bottom quintile bears a burden of 6.0 percent when inequality is measured on an income basis, falling steadily to 1.2 percent for the top quintile. Lower-income households spend a greater fraction of their income on energy-intensive consumption. One reason is that energy-intensive goods make up a slightly larger share of spending for lower-income households. Another is that lower-income households spend a larger fraction of their income due to lower or even negative saving rates—on average lower-income households spend more than their income. Dividing households into consumption quintiles rather than income quintiles greatly reduces this second effect, and hence the distributional burden is considerably less regressive when measured based on consumption quintiles. In

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[24] The results discussed below are broadly consistent with those presented by Burtraw et al. (2009), who look at the incidence of federal cap-and-trade policies under alternative revenue uses using a model with considerable disaggregation by households and region.

this case, the bottom quintile bears a burden of 3.3 percent while the top quintile bears a burden of 1.5 percent.

Indexing the tax-and-transfer system for inflation provides an automatic offset for part of the burden of the policy, and the pattern of this gain across households is the same across policy scenarios. As the prices of energy-intensive goods rise, indexing for inflation causes an increase in transfers (or decrease in taxes paid, for indexing of tax brackets and other elements of the tax system). Averaged across all households, the benefit from indexing for inflation is about 0.3 percent of income, or about one-seventh of the average burden from higher energy prices (1.9 percent). The portion of the burden of energy prices offset by indexing for inflation varies relatively little across income quintiles—for example, it offsets roughly one-seventh of the burden for the bottom quintile, about one-fifth for the middle, and one-eleventh for the top quintile.[25]

For the proportional income tax case (Figures 2a and 3a), by definition the gains from the tax cut are the same for each quintile: roughly 1.7 percent of income for each group. The overall net burden under this policy as a percentage of income is highest for the bottom quintile and falls steadily as one moves up the income distribution, given that revenue recycling does nothing to offset the regressive effect of higher energy prices. For income-based quintiles, the net burden varies between 3.5 and –0.6 percent across the lowest and highest quintiles, while for consumption-based quintiles, it varies from 1.2 to –0.3 percent.

For the cap-and-dividend policy (Figures 2b and 3b), the distribution of the policy dividend is highly progressive, given that all households receive the same absolute cash rebate. As a result, even though the overall cost of this policy is much higher than in the proportional income tax cut case, the bottom three quintiles experience smaller net burdens under cap-and-dividend. In fact, the bottom two quintiles have a negative net burden (under either income- or consumption-based quintiles). This illustrates the stark trade-off between efficiency and distribution: lower-income groups are much better off under cap-and-dividend than they are under a proportional income tax cut, but the overall welfare cost of the policy is dramatically higher.

The policy with free allowance allocation to firms (Figures 2c and 3c) does nothing to offset the regressive effect of higher energy prices—in fact, the distribution of rent income is itself regressive, for the most part, given that for better-off households, capital is typically a larger share of their income. Comparing this case to either the proportional income tax cut or the cap-and-

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[25] For reasons analogous to those discussed in footnote 22, the net burden on each quintile is independent of the choice of price normalization. But the decomposition of that net burden into indexing for inflation and other components does depend on the normalization.

dividend case reveals no trade-off between efficiency and distribution. Freely allocating permits to firms results in a similarly regressive distribution of net burden to the proportional income tax case but a much higher overall cost because it fails to exploit the revenue-recycling effect. In fact, every income quintile is better off under the proportional income tax cut than under free permits. Conversely, the cap-and-dividend case results in a much more progressive distribution of net burdens than free permits but has a similar (even slightly lower) overall cost.

Under the distribution-neutralizing change (Figures 2d and 3d), the tax change is designed to be sufficiently progressive to exactly offset the regressive burden of higher energy prices, thus making the distribution of the net burden of the policy proportional to income. This case falls between the proportional tax cut and cap-and-dividend cases, in terms of both efficiency and distribution: the overall cost is lower than under cap-and-dividend but higher than under the proportional tax cut, and the distribution of burden is less progressive than under cap-and-dividend but less regressive than under the proportional tax cut.

5. Conclusions

The allocation and use of rents created under cap-and-trade programs (or revenues under an emissions tax) can hugely affect the overall efficiency and distributional effects of carbon policy. Within the range of options we consider for the use of revenue, in a case where the direct cost of the carbon restriction itself is $9 billion per year in 2020, the overall welfare cost of the policy ranges from –$6 billion per year to $53 billion per year. The distribution of that cost ranges from highly progressive (with the bottom two income quintiles bearing a negative burden) to highly regressive (with the top two quintiles bearing a negative burden).

In general, there is a clear trade-off between efficiency and distribution. Using policy revenues to fund cuts in marginal income tax rates is highly efficient but leads to a regressive distribution of the net burden. At the other end of the range, the cap-and-dividend approach has a far higher overall cost but leads to a highly progressive distribution. And a distribution-neutralizing tax change represents a middle ground for both efficiency and distributional effects.

This trade-off does not hold for free permit allocation to firms in affected industries, which has a high overall cost and regressive distribution of that cost. But this case represents an efficiency-distribution trade-off along a different dimension, addressing distributional concerns across firms in different industries rather than across households in different income groups. Thus, while this type of allocation is both inefficient and regressive, it may have more political traction.

More generally, our discussion underscores that the case for cap-and-trade without revenue recycling is more fragile than generally realized (at least for medium-term levels of emissions controls envisioned in recent climate bills). Our calculations imply the average cost of reducing domestic, energy-related CO_2 when policy rents are not used to cut distortionary taxes is around \$90 per ton—far above most estimates of the benefits per ton of CO_2 reductions (e.g., Aldy et al. forthcoming; U.S. IAWG 2010).[26] In contrast, the average cost is –\$12 per ton when efficiency gains from the revenue-recycling effect are fully exploited (without even including any climate benefits). In our compromise cases, where the carbon policy is neither regressive nor progressive, the average cost per ton reduced is \$18–\$42.

Given these trade-offs and the potentially huge consequences for both efficiency and distribution, the use of revenue needs more attention in analyzing carbon policy. Future research on creative policy designs that balance efficiency, distribution, and political feasibility could be highly valuable.

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[26] Nonetheless, many arguments address the need for moving ahead with a cap-and-trade program, even if it fails a narrowly defined cost–benefit test in the early years. For example, the benefit to cost ratio could easily become favorable over time as the policy is tightened and a greater share of policy rents are used in efficiency-enhancing ways; putting a price on carbon could have important long-run benefits in terms of encouraging clean technology development; and action by the United States on climate policy could help to spur similar programs in other countries.

Appendix: Analytical Derivations

A. Deriving Equation (10)

We follow the usual two-step procedure for obtaining the marginal welfare effects of policy changes. First we solve the household's optimization problem. Then we obtain the welfare effects of a marginal change in the emissions price by totally differentiating the household's indirect utility, accounting for the household's behavior as well as changes in prices, taxes, and lump-sum income. Finally, we integrate over marginal welfare effects to obtain the effects of non-marginal policy changes.

(i) Household optimization. From (1)–(3), the optimization problem for household group *i* is given by:

(A1) $$V_i(p_E, p_F, p_C, t_i, G_i, \pi_i) =$$

$$\underbrace{Max}_{X_{iE}, X_{iF}, X_{iC}, L_i} \quad u_i(X_{iE}, X_{iF}, X_{iC}, L_i, G^{PUB})$$

$$+\lambda_i\left[(1-t_i)\Gamma_i + G_i + \pi_i - \sum_j p_j X_{ij}\right] \quad ,$$

where $V_i(.)$ denotes the indirect utility function and λ_i is the marginal utility of income. Using the definition of taxable income in (3a), this optimization yields the first-order conditions, demand, and labor supply functions:

(A2) $$\frac{\partial u_i}{\partial X_{iE}} = \lambda_i p_E\,, \quad \frac{\partial u_i}{\partial X_{iF}} = \lambda_i p_F(1-t_i)\,, \quad \frac{\partial u_i}{\partial X_{iC}} = \lambda_i p_C\,, \quad \frac{\partial u_i}{\partial L_i} = \lambda_i(1-t_i)w_i\,,$$

$$X_{ij} = X_{ij}(p_E, p_F, p_C, t_i)\,, \qquad L_i = L_i(p_E, p_F, p_C, t_i)\,.$$

To manipulate the analytical derivations below, we obtain the following additional expressions by totally differentiating the expression in (A1) with respect to arguments of the indirect utility function, and using the conditions in (A2). This gives:

(A3) $$\frac{\partial V_i}{\partial p_j} = -\lambda_i X_{ij}\,, \quad \frac{\partial V_i}{\partial t_i} = -\lambda_i \Gamma_i\,, \quad \frac{\partial V_i}{\partial G_i} = \frac{\partial V_i}{\partial \pi_i} = \lambda_i\,.$$

(ii) Welfare effects of marginal policy changes

Aggregate welfare is given by the sum of individual utilities, $\sum_i V_i$. Totally differentiating this with respect to a change in the emissions price and expressing in monetary units gives:

(A4) $$\sum_i \frac{1}{\lambda_i}\frac{dV_i}{d\tau} = \sum_i \frac{1}{\lambda_i}\left[\sum_j \frac{\partial V_i}{\partial p_j}\frac{dp_j}{d\tau} + \frac{\partial V_i}{\partial t_i}\frac{\partial t_i}{\partial \tau} + \frac{\partial V_i}{\partial G_i}\frac{dG_i}{d\tau} + \frac{\partial V_i}{\partial \pi_i}\frac{d\pi_i}{d\tau}\right].$$

Next, we discuss expressions for some of the individual terms in (A4).

First consider $dp_j / d\tau$. Differentiating (5) with respect to τ gives:

(A5) $$\frac{dp_H}{d\tau} = \left(\tau - c'\right)\frac{dz}{d\tau} + z\ .$$

However the first term cancels, assuming that firms equate marginal abatement costs c' to the emissions tax. Differentiating (4) with respect to τ, and using (A5), gives:

(A6) $$\frac{dp_j}{d\tau} = \rho_j z\ .$$

Using (A6), (A3) and (6), the first term in (A4) simplifies as follows:

(A7) $$\sum_i \frac{1}{\lambda_i}\sum_j \frac{\partial V_i}{\partial p_j}\frac{dp_j}{d\tau} = -Z\ .$$

Next, take the second and third terms in (A4), and substitute using (A3) to give:

(A8) $$\sum_i \left\{\frac{\partial V_i}{\partial t_i}\frac{\partial t_i}{\partial \tau} + \frac{\partial V_i}{\partial G_i}\frac{dG_i}{d\tau}\right\}\frac{1}{\lambda_i} = \sum_i \left\{\frac{dG_i}{d\tau} - \Gamma_i\frac{dt_i}{d\tau}\right\}.$$

Now we totally differentiate the government budget constraint in (8) with respect to τ, holding G^{PUB} constant but allowing t_i and G_i to vary, where $dt_i / d\tau = dt / d\tau$. This gives, after expressing changes in Z as a total differential:

(A9) $$\sum_i \frac{dG_i}{d\tau} = (1-\phi)\left(Z + \tau\frac{dZ}{d\tau} + \sum_i t_i\frac{\partial \Gamma_i}{\partial \tau}\right). + \sum_i\left(\Gamma_i + t_i\frac{\partial \Gamma_i}{\partial t_i}\right)\frac{dt}{d\tau} + \sum_i t_i\frac{\partial \Gamma_i}{\partial G_i}\frac{dG_i}{d\tau}$$

From the definition of the marginal excess burden (*MEB*) in (10b):

(A10) $$\sum_i \left(\Gamma_i + t_i \frac{\partial \Gamma_i}{\partial t_i} \right) = \frac{\sum_i \Gamma_i}{1+MEB}\,.$$

Substituting (A10) in (A9), multiplying through by 1+*MEB* and subtracting $\sum_i \Gamma_i dt / d\tau$ gives:

(A11) $$\begin{aligned} \sum_i \left(\frac{dG_i}{d\tau} - \Gamma_i \frac{dt}{d\tau} \right) &= (1+MEB)\left(\left(Z + \tau \frac{dZ}{d\tau} \right)(1-\phi) + \sum_i t_i \frac{\partial \Gamma_i}{\partial \tau} \right). \\ &\quad + (1+MEB)\sum_i t_i \frac{\partial \Gamma_i}{\partial G_i}\frac{dG_i}{d\tau} - MEB \sum_i \frac{dG_i}{d\tau} \end{aligned}$$

Finally, from differentiating (7) with respect to τ, and using (A3), the last term in (A4) can be expressed as

(A12) $$\sum_i \frac{1}{\lambda_i}\frac{\partial V_i}{\partial \pi_i}\frac{d\pi_i}{d\tau} = \phi \left(Z + \tau \frac{dZ}{d\tau} \right),$$

where we have used $\sum_i \theta_i = 1$.

Substituting (A7), (A8), (A11), and (A12) in (A4), then expressing utility losses as a positive number (i.e., welfare cost) gives:

(A13) $$\begin{aligned} -\sum_i \frac{1}{\lambda_i}\frac{dV_i}{d\tau} &= -\tau \frac{dZ}{d\tau} - MEB \cdot \left[(1-\phi)\left(Z + \tau \frac{dZ}{d\tau} \right) - \sum_i \frac{dG_i}{d\tau} \right] \\ &\quad - (1+MEB)\cdot \sum_i t_i \frac{\partial \Gamma_i}{\partial \tau} - (1+MEB)\cdot \sum_i t_i \frac{\partial \Gamma_i}{\partial G_i}\frac{dG_i}{d\tau}\,. \end{aligned}$$

(iii) Welfare effects of non-marginal policy changes

Integrating the first term in (A13) between 0 and τ, assuming $dZ / d\tau$ is constant, gives:

(A14) $$-\frac{dZ}{d\tau}\frac{\tau^2}{2}\,.$$

Again, given $dZ / d\tau$ is constant, $-(dZ / d\tau)\tau = Z_0 - Z$. Hence we obtain WC^{HT} in (10a).

We take the *MEB* as constant over the relevant range, which is reasonable given that proportional changes in income tax rates are relatively small. Integrating marginal emissions tax revenue $(1-\phi)(Z + \tau \cdot dZ / d\tau)$ over an emissions tax rising from 0 to τ simply gives revenue raised by the tax, $(1-\phi)\tau Z$.

And integrating the marginal change in the transfer payment for household group *i* over the tax increase simply gives the total change in transfer payment $G_i - G_i^0 = \Delta G_i$. Hence we obtain WC^{RR} in (10a).

From the third component of (A13), $\partial \Gamma_i / \partial \tau = (\partial \Gamma_i / \partial \overline{p})(\partial \overline{p} / \partial \tau)$. Taking a small change in the emissions price this expression becomes $(\partial \Gamma_i / \partial \overline{p}) \Delta \overline{p}$. Hence we obtain the first expression for WC^{TI} in (10a).

Substituting expressions for $\eta_i^{\overline{p}}$ and α_i^T from (10b), gives:

$$\text{(A15)} \quad WC^{TI} = (1 + MEB) \sum_i \alpha_i^T t_i \eta_i^{\overline{p}} \Delta \overline{p} \sum_i I_i \ ,$$

where the general price level is normalized to unity. The burden of the emissions price $\tau(Z + \Delta Z / 2)$ is fully passed forward into higher product prices, therefore $\Delta \overline{p} = \tau(Z + \Delta Z / 2) / \sum_{ij} X_{ij}$. Making this substitution and $\sum_{ij} X_{ij} = \sum_i I_i$ in (A15) gives the second expression for WC^{TI} in (10a).

Finally, again if we approximate by taking t_i and $\partial \Gamma_i / \partial G_i$ as constant over the relevant range, then integrating over the last term in (A13) gives

$$\text{(A16)} \quad -(1 + MEB) \cdot \sum_i t_i \frac{\partial \Gamma_i}{\partial G_i} \Delta G_i \ .$$

Substituting out $\partial \Gamma_i / \partial G_i = \partial \Gamma_i / \partial I_i$ using the taxable-income elasticity with respect to income in (10b), gives the last expression WC^{INC} in (10a).

B. Deriving equation (11)

Equation (11) comes from the effect on utility from small changes in each argument of $V_i(.)$ in equation (A1), after substituting (A3), and dividing by $\lambda_i I_i$.

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Table and Figures

Table 1. Summary of Baseline Data

(projections for year 2020 with monetary data in year 2008 dollars)

Household data	Income quintile					Average
	1	2	3	4	5	
Income, $	11,307	22,882	46,638	81,467	181,626	68,784
Consumption, $	22,566	34,187	47,835	66,202	108,573	55,873
Burden of carbon tax						
as percentage of income	6.03%	4.27%	2.71%	1.87%	1.16%	1.59%
as percentage of consumption	3.02%	2.86%	2.64%	2.31%	1.94%	1.96%
Fraction of stockholder wealth owned	2.63%	8.92%	8.63%	19.99%	59.84%	
Lump-sum transfer component of tax, $	4,048	6,762	9,404	11,909	7,949	8,014

	Consumption quintile					Average
	1	2	3	4	5	
Income, $	18,204	35,476	53,203	82,719	145,079	66,936
Consumption, $	19,253	34,605	49,644	70,428	126,173	60,020
Burden of carbon tax						
as percentage of income	3.27%	2.74%	2.27%	1.87%	1.54%	1.64%
as percentage of consumption	3.09%	2.81%	2.43%	2.20%	1.77%	1.83%
Fraction of stockholder wealth owned	1.60%	3.30%	12.85%	24.63%	57.62%	
Lump-sum transfer component of tax, $	3,453	7,716	11,085	13,743	10,314	9,262

	Income or Consumption quintile					Average
	1	2	3	4	5	
Income tax rate	17%	33%	40%	44%	41%	40%
Taxable income elasticities						
with respect to taxes	0.20	0.22	0.25	0.28	0.35	0.31
with respect to price level	0.15	0.15	0.15	0.15	0.15	0.15
with respect to income	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20

Other data	
Marginal excess burden of taxation	0.27
BAU CO_2 emissions, billion tons	6.0
Emissions price, $/ton	33
Reduction in emissions from BAU	9.0%
Policy rents/revenues, $billion	180

Source. See text.

Note that averages differ slightly between the income and consumption quintile cases, due to dropping households with consumption under $7,500

Figure 1. Decomposition of Efficiency Costs under Alternative Policies

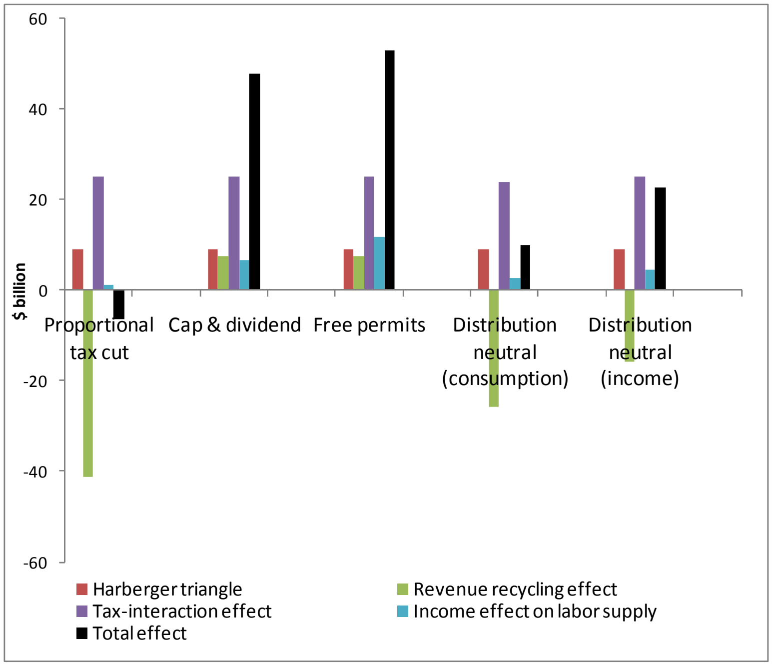
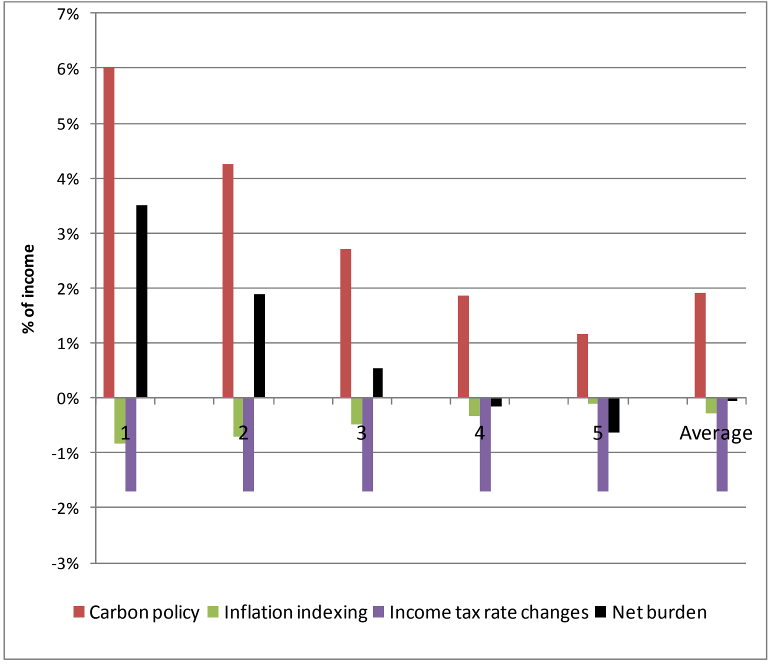
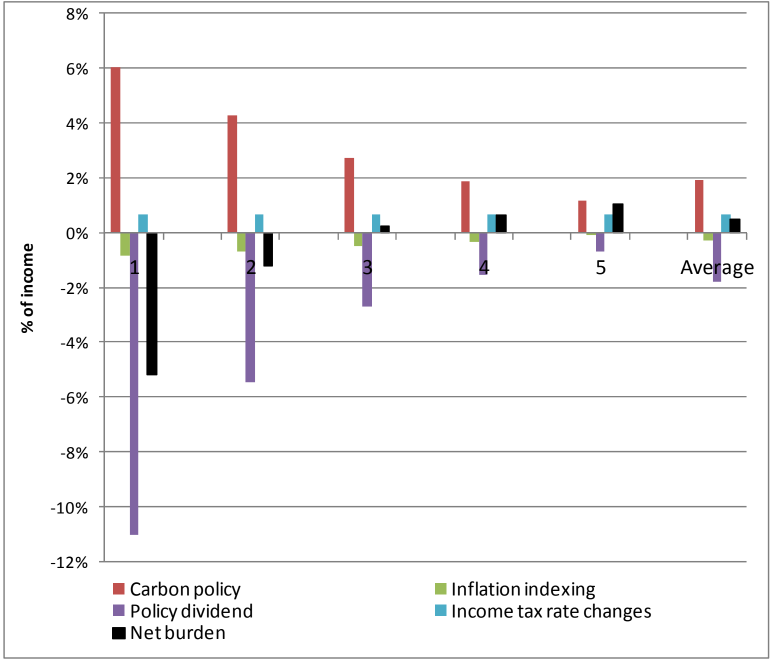


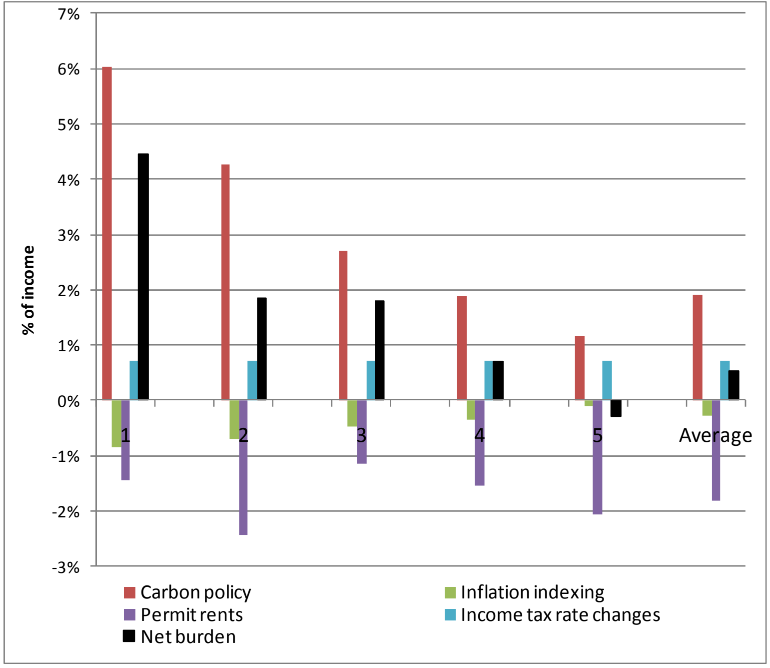
Figure 2. Decomposition of Net Burden by Income Quintile under Alternative Policies

(a) Proportional tax cut

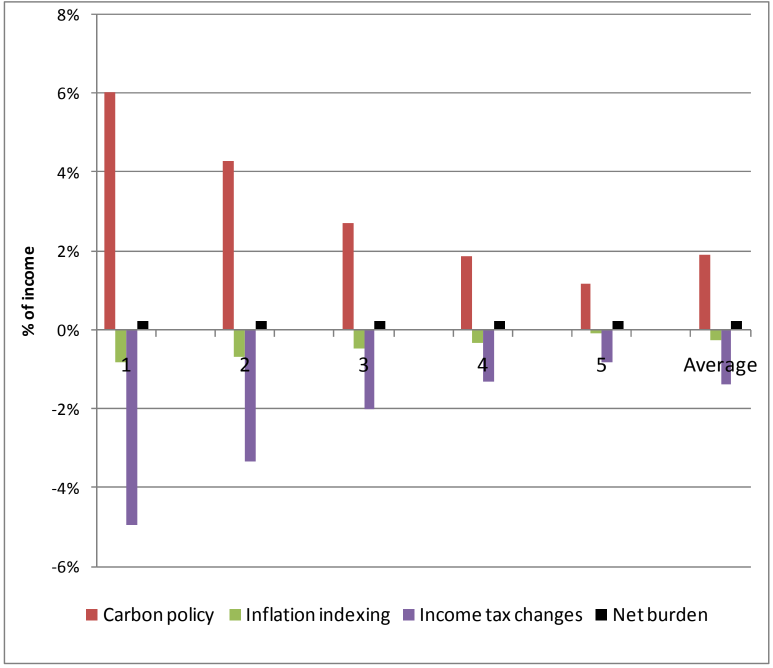


(b) Cap-and-Dividend





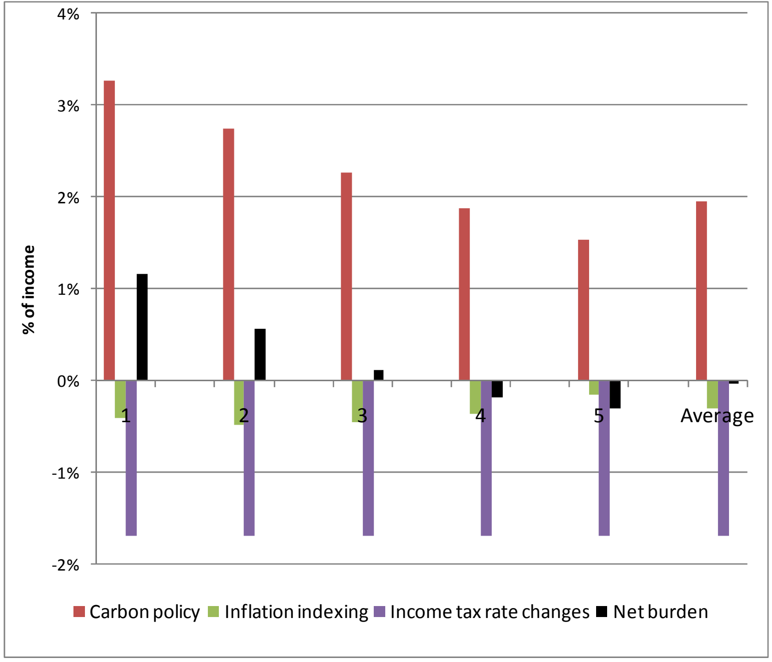
(c) Free Permit Allocation



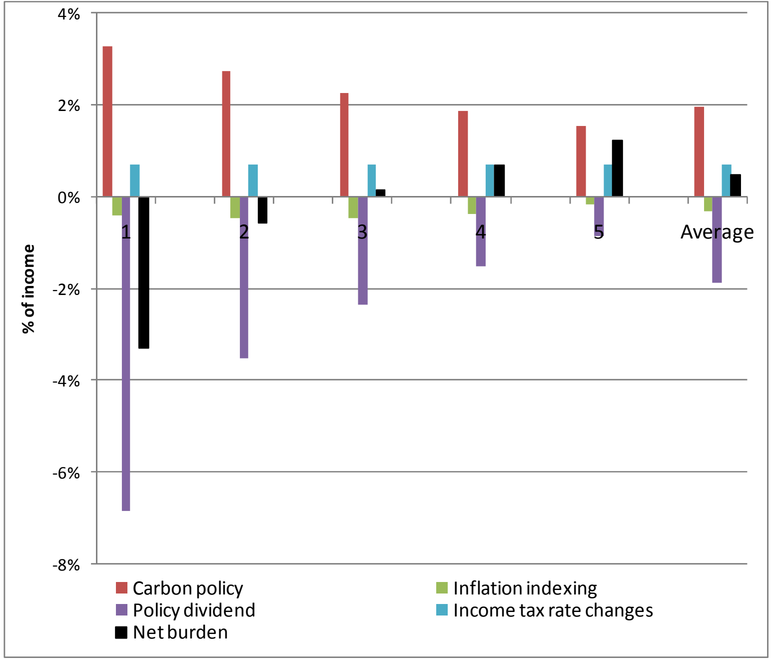
(d) Distribution-Neutral

Figure 3. Decomposition of Net Burden by Consumption Quintile under Alternative Policies

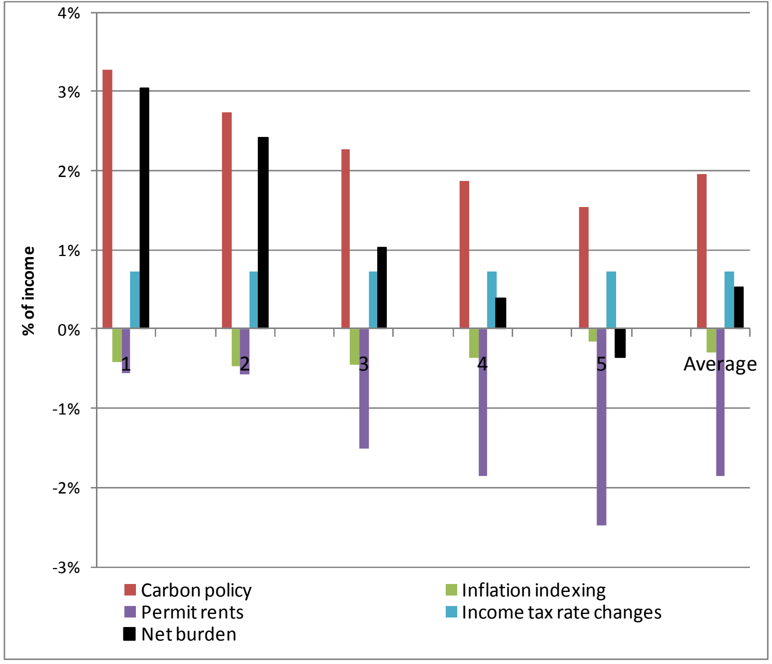
(a) Proportional tax cut



(b) Cap-and-Dividend



(c) Free Permit Allocation



(d) Distribution-Neutral