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Impacts of a carbon tax across US household income groups: What are the equity-efficiency trade-offs?

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ABSTRACT

This paper assesses the impacts across U.S. household income groups of carbon taxes of various designs. We consider both the source-side impacts (reflecting how policies affect wage, capital, and transfer incomes) as well as the use-side impacts (reflecting how policies alter the prices of goods and services purchased by households). We apply an integrated general equilibrium framework with extended measures of the source- and use-side impacts that add up to the overall welfare impact. Our results indicate that the distributional impacts depend importantly on the nature of revenue-recycling and the treatment of transfer income. In the absence of targeted compensation to achieve distributional objectives, the use-side impacts tend to be regressive while the source-side impacts are progressive, and the progressive source-side impacts tend to offset fully the regressive use-side impacts. Both impacts are considerably larger when one employs the more comprehensive welfare measures introduced in this study. The efficiency costs of targeted compensation to achieve distributional objectives depend critically on the recycling method and compensation target. These costs are an order of magnitude higher when the remaining revenues after compensation are used for corporate income tax cuts, compared with costs when remaining revenues are used other ways. Efficiency costs also rise dramatically when targeted compensation extends beyond the lowest income quintiles.

1. Introduction

A nationwide carbon tax — a tax on fossil fuels in proportion to their carbon content — is a much discussed potential instrument for mitigating future climate change. In nearly all uses, the carbon dioxide (CO_2) emissions resulting from the combustion of fossil fuels or of their refined products are proportional to their carbon content. Hence a carbon tax is implicitly a tax on emissions of CO_2, a principal greenhouse gas. Such a tax reduces CO_2 emissions by inducing producers and consumers to substitute away from the use of these fuels or carbon-intensive products.

Economists tend to prefer the carbon tax over other potential instruments for addressing climate change in view of its potentially greater cost-effectiveness: its apparent ability to achieve given targets for emissions reductions at lower cost than other policy approaches, such as technology mandates or subsidies to low-carbon sources of energy.[1] However, the distribution of the policy's impacts and the associated implications for fairness are also important considerations. The

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[1] Several attributes of a carbon tax suggest its greater cost-effectiveness. One is flexibility is as follows: rather than require a particular way to reduce emissions, a carbon tax gives firms flexibility to find the lowest-cost way to achieve the reductions. A second is the ability of a carbon tax (if broad-based) to promote equality of marginal abatement costs across firms that directly or indirectly use carbon-based fuels. Such equality is a condition for minimizing the aggregate costs of emissions abatement. On this, see, for example, Fischer et al. (2001). Third, a carbon tax tends to encourage more demand-side conservation than conventional regulations that impose the same effective marginal cost of abatement. This is because, in contrast with conventional regulations, a carbon tax not only promotes emissions reductions but also charges for remaining emissions; this helps ensure a more efficient output price and a more efficient level of demand-side conservation. See Goulder and Parry (2008) for a discussion of this point. Finally, because it brings in revenues, a carbon tax creates opportunities for revenue recycling in the form of cuts in the rates of preexisting distortionary taxes. As discussed by Oates (1993), Fullerton and Metcalf (2001), and others, this can reduce policy costs.

distribution of a carbon tax's impacts across household income groups, in particular, is a central consideration.[2]

The impacts on households can be decomposed into what public finance economists have termed *use-side* and *source-side* effects. The use-side impact is the effect on purchasing power or well-being that stems from changes in the prices of the goods and services that households purchase. A carbon tax alters the relative prices of the goods and services that households purchase. The prices of goods and services that are more carbon-intensive in their production will generally rise relative to prices of other goods and services. This has distributional consequences: households that rely relatively more on those goods will experience a greater reduction in real income than households less reliant on those goods.

The source-side impact is the change in purchasing power or well-being attributable to policy-induced changes in a household's nominal labor, capital, and transfer income. A carbon tax generally will affect (positively or negatively) after-tax wages, returns to capital, and transfers. This differently affects households to the extent that their reliance on these different forms of income differs.

This paper assesses the distribution of the impacts across US household income groups of carbon taxes of various designs, taking into account both the use- and source-side impacts.[3] In addition to exploring the absolute impacts on various household income groups, we examine the relative impacts, such as the extent to which the impacts are regressive or progressive. We also assess the potential aggregate costs of reducing or avoiding regressivity, or of avoiding absolute losses of welfare to households in the lowest income groups.

Our paper builds on earlier literature that has considered the source- and use-side impacts of carbon taxes. Some studies focus exclusively on the use side, and these studies tend to obtain regressive impacts. Fremstad and Paul (2017) and Grainger and Kolstad (2010) assess the use-side impacts using input-output models[4]; Mathur and Morris (2014) consider these impacts using a general equilibrium model. In contrast, Rausch et al. (2011), Fullerton et al. (2011), and Williams et al. (2015) examine both use- and source-side effects. These analyses tend to find progressive source-side impacts that fully offset the use-side impacts, causing the overall impacts of carbon taxes to be progressive.[5]

The present paper builds on this work in four ways. First, it offers an especially consistent theoretical framework and numerical approach. The theoretical framework fully integrates the source- and use-side impacts on utility while revealing their separate contributions to welfare. In addition, rather than employ separate empirical models to measure the two types of impacts, this study applies a single general equilibrium modeling framework to assess the impacts on the source and use sides as well as quantify the efficiency costs of achieving various distributional goals.

Second, in contrast with earlier work, our analysis develops and applies more complete measures of the household welfare impacts. The measures of source-side impacts account for the effects of policies on the value of households' time (labor and leisure), rather than just on the value of the labor income. And the measures of use-side impacts account for policy effects on the price of leisure (another "good" that households consume) in addition to the prices of other goods and services. To reveal the significance of these broader measures, we compare the welfare impacts that they yield with the impacts that result when the often-used narrower measures are applied.

Third, whereas previous studies have tended to focus on the distributional impacts at a single point in time (usually the present), we exploit the multiperiod property of our numerical model to examine changes in the distributional impacts over time.

Fourth, we compare policies with and without targeted compensation to assess the efficiency costs of avoiding certain distributional outcomes.

We find that under a range of recycling methods, the source-side impacts are generally progressive, while the use-side impacts are consistently regressive. The progressive source-side impacts tend to offset fully the regressive use-side impacts, so that the overall impacts are either slightly progressive or close to proportional. Under all of the forms of recycling we have considered, the lowest income quintile enjoys a positive source-side impact sufficient to enable the household to experience a positive overall welfare impact from the climate change policy.[6] While several forms of revenue-recycling exert a progressive influence, the overall impacts are slightly progressive even in the absence of recycling — that is, when the government retains the revenue to finance public expenditure.

We also find that both the source- and use-side impacts are considerably larger once one takes into account the more comprehensive measures that we employ in this study. Inflation-indexed transfers avoid what otherwise would be regressive overall impacts of the carbon tax by providing additional nominal transfers to compensate for the higher overall consumer prices induced by the tax.

The efficiency sacrifices required to avoid adverse welfare impacts depend critically on the scope of compensation and the opportunity cost associated with using some carbon tax revenues for compensation rather than for economy-wide tax cuts. In particular, under a policy requiring compensation sufficient to prevent a welfare loss by representative households in the lowest two income quintiles, the policy costs are an order of magnitude higher when such compensation applies revenues that otherwise would be used for corporate tax cuts, as compared with cases when the revenues otherwise would be used for individual income or payroll tax cuts.

The rest of the paper is organized as follows. Section 2 presents an analytical model of household behavior and utility that shows the channels through which a carbon tax yields the source- and use-side utility impacts. The next two sections focus on the numerical model's structure (Section 3) and data and parameters (Section 4). Sections 5–9 present and evaluate the numerical model's results for the carbon tax's impacts. Section 5 provides the economic outcomes in our reference (no-policy-change) case. Section 6 describes the carbon tax's aggregate impacts on emissions, prices and output. Section 7 then examines and interprets the distribution of impacts across household groups. Sections 8 evaluates the efficiency costs of achieving certain distributional objectives, while Section 9 focuses on the importance of government transfers to the distributional results. Section 10 offers conclusions.

2. Defining and measuring the welfare impacts

Here we derive analytical expressions for the source- and use-side impacts of a carbon tax (or other policy change) on a household that maximizes utility over an infinite horizon. We show that these two impacts combine to produce the total impact on utility. We then indicate how we obtain a quantitative measure of these impacts.

[2] The impacts across producers or industries are also relevant to fairness (and to political feasibility). A large number of studies have investigated the potential impacts of a carbon tax across industries. See, for example, Jorgenson et al. (2013). Since industry impacts are ultimately felt by workers, managers, and owners of firms, in some ways the question of fairness ultimately must involve relative impacts across individuals rather than firms.

[3] The public finance literature includes numerous assessments of use- and source-side impacts of other tax policies. See, for example Fullerton and Rogers (1993), Randolph (2006), and Toder and Rosenberg (2010).

[4] Grainger and Kolstad (2010) show that the regressivity of the use-side impact varies with different recycling methods.

[5] Rausch et al. (2011) find that the source-side impact is progressive and sufficient to overcome the regressive use-side impact when the carbon tax policy involves lump-sum recycling. Fullerton et al. (2011) find that progressivity in US transfer program indexing significantly offsets regressivity on the use side. Williams et al. (2015) show that the source-side impact is highly progressive when revenues are recycled as lump-sum payments to households, making the overall impact progressive. Although Cronin et al. (2017) focus mainly on the use-side impact, they consider income transfers and argue that a carbon tax's impact is progressive once one accounts for the indexing of transfers.

[6] This is not to suggest that all households in the lowest quintile would experience a welfare gain. Given the heterogeneity of expenditure patterns and income sources within a quintile, the welfare impacts within a quintile will vary.

2.1. The utility-maximization problem

Consider the following dynamic (infinite-horizon) utility-maximization problem. A household receives an initial nonhuman wealth endowment W_0 and an annual labor endowment $\bar{l}_t$, and chooses "full consumption" C_t to maximize its lifetime utility, taking the price of consumption and the returns to nonhuman and human wealth as given. Utility is given by

$$U = \sum_{t=0}^{\infty} \beta^t U(C_t) \tag{1}$$

Nonhuman wealth evolves according to

$$W_{t+1} - W_t = \overline{w}_t \bar{l}_t + \overline{r}_t W_t - P_t C_t \tag{2}$$

The left-hand side is the change in nonhuman wealth over two successive periods. This change is equal to after-tax wage income plus capital income minus the value of full consumption. In the above expression, P_t is the price of full consumption, $\overline{w}_t$ is the after-tax wage, and $\overline{r}_t$ is the after-tax return on capital.[7]

The intertemporal budget constraint is

$$\sum_{t=0}^{\infty} [P_t C_t] d_t = W_0 + \sum_{t=0}^{\infty} \left[\overline{w}_t \bar{l}_t\right] d_t \tag{3}$$

where

$$d_t = \prod_{u=0}^{t} [1 + \overline{r}_u]^{-1} \tag{4}$$

The transversality condition,

$$\lim_{t\to\infty} W_{t+1} d_t = 0 \tag{5}$$

is imposed to rule out eternal speculative bubbles. Eq. (3) states that the present value of full consumption must not exceed the sum of financial and human wealth, where the latter is the present value of the time endowment.[8]

The first-order conditions for the utility-maximization problem are

$$\frac{\partial L}{\partial C_t} \quad : \quad U_C(C_t) = \lambda_t P_t \tag{6}$$

$$\frac{\partial L}{\partial W_{t+1}} \quad : \quad \lambda_t = \beta(1 + \overline{r}_{t+1})\lambda_{t+1} \tag{7}$$

where λ_t is the Lagrange multiplier on the budget constraint and represents the shadow value of full consumption. Eq. (7), the intertemporal Euler condition, equates the discounted shadow value of consumption over time. Given the terminal shadow value of consumption in period T, and the vector of the prices in all future periods, we can determine the optimal level of full consumption in any given period t,

$$C_t = C_t\left(P, \overline{r}, \lambda^T\right) \tag{8}$$

[7] In the numerical model, in each period t full consumption C_t is a composite of leisure and $\overline{C}_t$, a composite of consumption of specific goods and services. P_t, the price of full consumption, is a function after-tax wage and the price of a composite of consumption of specific goods and services. Leisure is valued at the opportunity cost of time not spent working. The price of $\overline{C}_t$ is the ideal price index based on the after-tax (or subsidy) prices of the 24 categories of consumer goods or services.

[8] We assume the intertemporal budget constraint is binding.

2.2. Defining the use- and source-side impacts

2.2.1. Key expressions

As indicated above, a carbon tax affects utility through its impact on returns to factors of production and on the prices of goods and services purchased. We measure the welfare effect of these changes using the *equivalent variation*, the change in wealth under reference case (status quo) conditions that would have the same impact on utility as that of the policy change.

Consider first these impacts in a one-period setting. Household i chooses consumption C_i to maximize utility $U_i = U(C_i)$ subject to the budget constraint $P_i C_i = Y_i$, where Y_i refers to nominal income from all sources (including transfers) for household i, and P_i refers to the price of the consumption good for that household.[9] The indirect utility function $U_i = V(Y_i, P_i)$ represents the household's utility, given income Y_i and price level P_i; the expenditure function $EX_i = EX(U_i, P_i)$ is the level of expenditure required to achieve utility U_i, given price level P_i.

Each household's overall welfare impact, when measured via the equivalent variation (EV), is the difference between two expenditure (EX) functions defined on prices and income:

$$EV = EX(U_1, P_0) - EX(U_0, P_0) \tag{9}$$

where $U_0 = V(Y_0, P_0)$ and $U_1 = V(Y_1, P_1)$; the subscripts 0 and 1 represent the reference (no-policy-change) and carbon-tax scenarios, respectively; and for brevity we have omitted the subscript identifying the particular household. Thus the welfare impact is the additional expenditure needed to achieve policy-case utility, given reference-case prices.

The overall welfare impact includes use- and source-side components, where the components differ according to whether goods prices or income is held fixed at reference-case levels. The use-side impact is the welfare change a household would experience as a result of the policy-induced changes in the nominal prices of goods and services consumed, if (counter to fact) its nominal income did not change. The source-side impact is the welfare change a household would experience as a result of the policy-induced changes in its nominal income, if (counter to fact) the nominal prices of the goods and services it consumes did not change. These definitions imply the following utility levels associated with the changes in goods prices and income:

$$U_{use} = V(Y_0, P_1) \tag{10}$$

$$U_{source} = V(Y_1, P_0) \tag{11}$$

Applying U_{use}, U_{source}, and the reference-case level of utility U_0, we can express the household's overall welfare as the sum of three equivalent variations:

$$EV = EV_{use} + EV_{source} + EV_{interaction} \tag{12}$$

where

$$EV_{use} = EX(U_{use}, P_0) - EX(U_0, P_0) \tag{13}$$

$$EV_{source} = EX(U_{source}, P_0) - EX(U_0, P_0) \tag{14}$$

and

$$EV_{interaction} = EX(U_1, P_0) - EX(U_{source}, P_0) + EX(U_0, P_0) - EX(U_{use}, P_0), \tag{15}$$

EV_{use}, EV_{source}, and $EV_{interaction}$ are the use-side, source-side, and interaction components of the overall welfare impact. In these EV expressions,

[9] In the numerical model, we organize households into income quintiles, and focus on the representative (median) household in each quintile.

prices and income are in nominal terms. The use- and source-side impacts in Eqs. (13) and (14) do not perfectly sum to the overall impact because of an interaction between the two effects. The $EV_{interaction}$ component in Eq. (12) is a residual that accounts for the interaction and allows the three EVs to sum exactly to the overall welfare impact. In our numerical simulations, the residual interaction term is very small, as indicated in Section 7.2.[10] For simplicity, in presenting the numerical results we embed the small interaction term within the use-side impact. Thus we employ the definition $EV_{\overline{use}} \equiv EV_{use} + EV_{interaction}$, where the subscript "$\overline{use}$" refers to the impact inclusive of the interaction term. From Eqs. (13) and (15), $EX(U_1,P_0) - EX(U_{source},P_0)$.

Define C_{source} as the household's utility-maximizing level of consumption under source-side conditions, that is, when $Y = Y_1$ and $P = P_0$. From the household's budget constraint, $C_{source} = Y_1/P_0$. Hence $U(C_{source}) = U(Y_1/P_0)$. By definition of the expenditure function, $EX(U_{source},P_0) = C_{source}P_0 = (Y_1/P_0)P_0 = Y_1$. By again using the budget constraint for policy-case expenditures, $EX(U_1,P_1) = C_1P_1 = Y_1$. Therefore, $EX(U_{source},P_0) = Y_1 = EX(U_1,P_1)$. Applying this equivalence yields

$$EV_{\overline{use}} = EX(U_1,P_0) - EX(U_1,P_1) \tag{16}$$

$$EV_{source} = EX(U_1,P_1) - EX(U_0,P_0) \tag{17}$$

In this one-period setting, a constant relative risk aversion (CRRA) utility function of the form $U = [1/(1-\sigma)]C^{1-\sigma}$ gives rise to simple numerical expressions for the use- and source-side impacts. The indirect utility function associated with this direct utility function is $U(Y,P) = [1/(1-\sigma)](Y/P)^{1-\sigma}$, and the associated expenditure function defined in terms of some given utility level U and price P is $EX(U,P) = P(1-\sigma)U^{\frac{1}{1-\sigma}}$. These expressions yield the following simple expressions for the welfare components of the overall welfare impact: $EV_{source} = Y_1 - Y_0$ and $EV_{use} = (P_0/P_1 - 1)Y_1$. In this CRRA case, the source-side impact is simply the change in nominal income, while the (combined) use-side impact is the percentage change in prices times policy-case nominal income.[11]

The numerical model that we apply below also employs a CRRA utility function, with the application in a multi-period framework. The use- and source-side impacts, along with the residual term, are dynamic analogs to the expressions immediately above. Here the expenditure functions represent the discounted present value of expenditure over some given (sometimes infinite) time-horizon, $t = \{0, \ldots, S\}$.

As indicated in expression (8), in the multi-period framework optimal consumption in each period can be written as a function of the vector of prices and interest rates in each period and a terminal shadow value of consumption: $C_t = C_t(P, \bar{r}, \lambda^S)$. The applicable expenditure function $EX(U, P, \bar{r})$ is the discounted present value of expenditures needed to achieve intertemporal utility U, given the price and interest rate vectors P and $\bar{r}$.

The expressions for EV and the expenditure functions from the one-period analysis translate directly into the corresponding expressions for the multi-period analysis. For example, while the one-period EV was equal to $EX(U_1,P_0) - EX(U_0,P_0)$, the analogous multi-period EV is $EX(U_1, P_0, \bar{r}_0) - EX(U_0, P_0, \bar{r}_0)$. In the expenditure functions, time-paths of prices and interest rates substitute for the price scalars in the one-period analysis. Incorporating the multi-period expressions for the expenditure functions and making use of the same connections between the budget constraint, consumption and prices as in the one-period case, in the multi-period context we again can decompose the overall welfare impact into its use- and source-side components:

$$EV_{\overline{use}} = EX(U_1, P_0, \bar{r}_0) - EX(U_1, P_1, \bar{r}_1) \tag{18}$$

$$EV_{source} = EX(U_1, P_1, \bar{r}_1) - EX(U_0, P_0, \bar{r}_0) \tag{19}$$

2.2.2. Significance of the numeraire

The carbon tax causes the prices of more carbon-intensive goods to rise relative to the prices of less carbon-intensive goods and services. Hence the price index P of the household's consumption basket will depend on the choice of numeraire. If, for example, a good with a low relative price (low carbon content) is chosen as numeraire, then the carbon tax will raise P_1 (the policy-case index) relative to P_0 (the reference-case index) for that household, since the tax causes most other prices to go up relative to the price of the numeraire good.[12] If, in contrast, a good with a very high relative price is chosen, the carbon tax will cause most other prices to go down relative to the numeraire, implying that P_1 will be below P_0.

By affecting the change in P, the choice of numeraire affects the division of the overall welfare impact into its use- and source-side components. To the extent that P increases (as determined by the relative carbon intensity of the numeraire good), the use-side impact becomes more negative, as indicated by a decrease in use-side utility U_{use} in expression (10). Correspondingly, the source-side impact becomes less negative, as a higher nominal value for income or wealth applies, consistent with the fact that the choice of numeraire does not alter *real* incomes (or wealth) in the general equilibrium — the numeraire choice only affects prices. Thus, the split in the overall welfare impact between the use- and source-side impacts depends on the numeraire. In the numerical assessment in Section 7, we indicate our preferred choice of numeraire and the rationale for that choice.

However, the overall welfare impact is independent of the numeraire choice. This is because a household's utility in the model only depends on real outcomes, and real outcomes in the model are independent of the choice of numeraire. Hence the choice of numeraire only affects the estimated magnitudes of the use- and source-side impacts and their relative contributions to the overall impact — not the overall welfare impact. We describe our preferred numeraire choice in Section 7.

2.3. Measuring the welfare impacts

To measure the welfare impacts, we need to evaluate the expenditure functions in expressions (18) and (19). For a given intertemporal utility level U and time-paths of P and $\bar{r}$, $EX(U, P, \bar{r}) = \sum_{t=0}^{S} [P_t C_t(P, \bar{r}, \lambda^S(U))] d_t(\bar{r})$, where $\lambda^S(U)$ is the terminal shadow value of consumption that satisfies $U = \sum_{t=0}^{S} \beta^t U(C_t(P, \bar{r}, \lambda^S))$, with $d_t(\bar{r}) = \prod_{u=0}^{t} [1 + \bar{r}_u]^{-1}$. To solve for the term $EX(U_1, P_0, \bar{r}_0)$ in the equivalent variation expression, we utilize the first-order conditions in Eqs. (6) and (7) and solve for the terminal shadow value of consumption λ^S such that $U_1 = \sum_{t=0}^{S} \beta^t U(C_t(P_0, \bar{r}_0, \lambda^S))$. To calculate welfare over the infinite horizon, we apply balanced growth path conditions on prices and quantities after some period T such that the steady state prices and quantities grow at fixed rates; the infinite-horizon expenditures are equal to the present discounted value of the transition expenditures and the present discounted value of the steady state expenditures.

10 The interaction term reflects the change in the marginal utility of income between the reference and policy cases. Because this change is small, the interaction term is quite small as well.

11 The pure use-side impact (i.e., without the interaction element) is equal to the percentage change in prices times reference-case nominal income.

12 Carbon content comprises both the carbon directly embodied in the inputs to the good or service and the carbon embodied in the goods and services employed to produce the inputs to the good or service.

3. The numerical approach

To assess the impacts of alternative carbon tax policies across U.S. household groups, we link two numerically solved models. This combination of models solves, for a representative household in each of five income groups, the utility-maximization problem of Section 2.

The two component models are the Goulder-Hafstead Environment-Energy-Economy (E3) model, a detailed general equilibrium model of the US economy, and the Disaggregated Household (DH) model, a model that distinguishes the economic behavior and welfare outcomes of five household income groups.

The E3 model solves for the prices of goods and factors, prices that contribute to the use- and source-side impacts. This model considers only a single representative household. Thus it does not distinguish the factor supply and consumption patterns of different household groups. To account for these differences and calculate the differing household impacts, we link the prices from the E3 model to the DH model. The E3 model's equilibrium prices are key inputs to the DH model.

Below we describe the structure of the models. Section 4 describes the data inputs for the models and the procedures employed to achieve a consistent linkage of the models.

3.1. Features specific to the E3 model

Computable general equilibrium (CGE) models have long been used to assess a wide range of tax policy options.[13] The essence of such models is their ability to solve simultaneously for the prices that equate supplies and demands in several goods and factor markets, accounting for the interactions of supplies and demands across these markets.[14] A CGE framework is especially well-suited for assessing the economy-wide impacts of a carbon tax, since the tax affects a large number of factor and goods markets and the overall impacts cannot be assessed by considering each of these markets independently.

Here we briefly describe elements of the CGE model (E3) used in this study.[15] This model comprises 35 distinct industries, a single representative household, and a single representative government for the US economy. It captures the interactions among these agents and solves for market-clearing prices in each period. Each agent has perfect foresight. The model is solved at annual intervals, beginning in the benchmark year, 2013.

Two features of this model are especially relevant for this study's evaluation of the impacts across households. First, it contains a detailed treatment of the US tax system. This allows us to measure how price and factor returns vary with how carbon tax revenue is recycled to households, which in turn enables us to measure, with the DH model, how the welfare impacts across households vary with the form of revenue recycling. Second, the E3 model recognizes the adjustment costs associated with installing (or removing) physical capital. Adjustment costs affect the distribution of policy impacts in two ways. They imply windfall gains to quasi-immobile capital, yielding impacts on capital incomes that differ across households according to differences in capital ownership. They also influence the rate at which capital stocks will adjust through time. This affects the speed at which the distributional impacts change with time.

3.1.1. The production sector and carbon dioxide emissions

The 35 industry categories identify the industries that supply carbon-based fuels and those that use these fuels intensively. The carbon-based primary fuels in the model are crude oil, natural gas, and coal. Producers sell these fuels to secondary energy producers, which in the model include electricity generators, natural gas distributors, and petroleum refiners. Electricity, natural gas, and petroleum products are then sold to other industries, the representative household, and the representative government. The production functions have the constant-elasticity-of-substitution (CES) functional form. Table 1 displays the E3 industries, their benchmark output levels, the value share of energy as an input into each industry's production, and the carbon intensity of each good.

In each industry, a representative firm combines variable inputs (labor, energy, and material inputs) and capital to produce its distinct output. Firms choose variable inputs to minimize unit costs and determine investment levels (subject to capital adjustment costs) to maximize the value of the firm.

The outputs from the 35 industries are intermediate inputs to the production of consumer goods. The input intensities of the producer goods used to create any given consumer good are fixed. Table 2 displays, for each consumer good, the benchmark expenditures on that good, the expenditure as a percentage of total consumption, and the carbon intensity. The carbon tax's impact on a consumer good's price depends significantly on the direct and indirect carbon intensity of the good. As indicated in the table, electricity, natural gas, motor vehicle fuels, and heating oil are the most carbon-intensive goods.

Technological progress takes the form of labor-augmenting Harrod-neutral technological change. Thus effective hours worked are actual hours worked adjusted for annual productivity gains. We assume a constant rate of technological change that is the same in all industries.

In the E3 model, the carbon tax is imposed as a tax on coal, crude oil, and natural gas inputs into production, where the tax is in proportion to the carbon content of each fuel. The representative household does not directly pay the carbon tax but generally faces higher prices on carbon-intensive goods as a result of the tax. The model calculates emissions by applying CO_2 emissions coefficients to the quantities of the fossil fuels purchased. This yields a close estimate of the ultimate CO_2 emissions associated with fossil fuel demand,[16] even though some emissions occur when refined fuels are combusted downstream.

3.1.2. The government sector

The government represents a combination of federal, state, and local governments in the United States. Government purchases of goods and services (including fixed investment expenditures), labor, and household transfers are financed through tax revenue and new debt issue. The government uses labor, capital, and intermediate goods to produce government services. In each policy experiment, real government spending in any given period is maintained at the same level as in the reference case. In most simulations,[17] we assume that government transfers are indexed so that they are maintained at reference case levels in real terms. Under a carbon tax policy involving lump-sum rebates, the rebates represent another government outlay.

Tax revenues are collected from households (personal income taxes and sales taxes) and firms (corporate income taxes, payroll taxes, and carbon taxes). All policies considered are revenue-neutral in the sense that the present value of revenues (net of tax-base impacts) must equal the present value of revenues returned to the private sector either through cuts in the marginal rates of existing taxes or through lump-sum rebates.[18]

[13] Leading CGE models for environmental policy evaluation are those described and applied Ross (2014) and Jorgenson et al. (2013).

[14] For a general introduction to CGE modeling, see, for example, Sue Wing and Balistreri (2018).

[15] A complete description, including a description of the solution method, is in Goulder and Hafstead (2017).

[16] Carbon content of fossil fuels accounts for ultimate CO_2 emissions, except for noncombustible uses of these fuels. In the United States, noncombustible uses currently account for less than 6% of fossil fuel use.

[17] In most policy simulations we adjust nominal transfers so that real transfers to each household remain at the same level as in the reference case, based on the consumer price index. However, to assess the distributional implications of transfer indexing we compare the results with fixed real transfers with the case where transfers are fixed in nominal terms.

[18] In individual years, the net revenues might slightly exceed or fall short of the revenues returned; such discrepancies are offset through lump-sum adjustments to taxes. In present value, these adjustments sum to zero.

Table 1
Benchmark outputs, energy inputs, and carbon intensities by industry.

Industry	Output[a]	Pct. of total output	Energy input[b]	Energy value share	Carbon intensity[c]
Oil extraction	277.3	1.1%	7.6	2.8%	5.53
Natural gas extraction	118.2	0.5%	2.9	2.5%	22.54
Coal mining	41.1	0.2%	2.4	5.8%	24.39
Electric transmission and distribution	389.2	1.5%	214.2	55.0%	3.47
Coal-fired electricity generation	74.5	0.3%	21.5	28.9%	7.24
Other fossil electricity generation	67.9	0.3%	36.7	54.0%	11.18
Non-fossil electricity generation	59.2	0.2%	0.1	0.1%	0.03
Natural gas distribution	136.2	0.5%	50.5	37.1%	7.98
Petroleum refining	719.2	2.8%	576.1	80.1%	4.37
Pipeline transportation	42.4	0.2%	3.2	7.5%	0.27
Mining support activities	47.5	0.2%	5.9	12.4%	0.75
Other mining	196.2	0.8%	5.9	3.0%	0.57
Farms, forestry, fishing	435.9	1.7%	26.4	6.1%	0.23
Water utilities	84.2	0.3%	2.0	2.4%	0.39
Construction	1365.6	5.2%	53.9	3.9%	0.44
Wood products	92.4	0.4%	3.0	3.3%	0.63
Nonmetallic mineral products	105.2	0.4%	6.4	6.1%	1.22
Primary metals	288.9	1.1%	19.8	6.8%	0.52
Fabricated metal products	337.3	1.3%	7.5	2.2%	0.29
Machinery and misc. manufacturing	1376.8	5.3%	13.5	1.0%	0.39
Motor vehicles	593.1	2.3%	4.8	0.8%	0.50
Food and beverage	817.7	3.1%	15.1	1.8%	0.36
Textile, apparel, leather	86.7	0.3%	1.7	1.9%	0.55
Paper and printing	231.1	0.9%	12.8	5.5%	1.02
Chemicals, plastics, and rubber	1010.5	3.9%	68.2	6.7%	0.16
Trade	2465.6	9.4%	38.7	1.6%	1.04
Air transportation	163.5	0.6%	36.8	22.5%	0.33
Railroad transportation	106.0	0.4%	6.2	5.8%	0.94
Water transportation	51.9	0.2%	9.8	18.8%	0.87
Truck transportation	288.1	1.1%	51.5	17.9%	0.51
Transit and ground passenger transportation	58.5	0.2%	5.9	10.1%	1.43
Other transportation and warehousing	291.5	1.1%	16.9	5.8%	0.37
Communication and information	1186.1	4.5%	5.3	0.4%	0.09
Services	9935.6	38.0%	125.8	1.3%	0.14
Real estate and owner-occupied housing	2606.8	10.0%	90.9	3.5%	0.16
Total	26,148.1	100%	1549.6	5.9%	

[a] In billions of 2013$.
[b] In billions of 2013$. Energy inputs include the values of purchases of fossil fuels, wholesale electricity, distributed natural gas, and refined petroleum products.
[c] Metric tons of carbon dioxide emissons per $1000 of value.

Table 2
Consumption good benchmark expenditures and carbon intensities.

Consumption category	Consumption[a]	Pct. of total consumption	Carbon intensity[b]
Motor vehicles	549.0	4.8%	0.26
Furnishings and household equipment	394.5	3.4%	0.35
Recreation	1022.1	8.9%	0.20
Clothing	425.8	3.7%	0.25
Health care	2372.1	20.7%	0.22
Education	277.1	2.4%	0.14
Communication	283.1	2.5%	0.10
Food	750.3	6.5%	0.38
Alcohol	124.7	1.1%	0.34
Motor vehicle fuels (and lubricants and fluids)	381.8	3.3%	2.98
Fuel oil and other fuels	26.6	0.2%	2.55
Personal care	245.3	2.1%	0.32
Tobacco	108.0	0.9%	0.37
Housing	1780.9	15.5%	0.16
Water and waste	136.4	1.2%	0.20
Electricity	169.1	1.5%	3.47
Natural gas	51.2	0.4%	7.96
Public ground	42.3	0.4%	0.47
Air transportation	49.5	0.4%	1.04
Water transportation	3.2	0.0%	0.73
Food services and accommodations	714.7	6.2%	0.14
Financial services and insurance	826.7	7.2%	0.14
Other services	700.5	6.1%	0.15
Net foreign travel	44.2	0.4%	1.01
Total	11,478.9	100.0%	

[a] In billions of 2013$.
[b] Metric tons of carbon dioxide emissions per $1000 of value.

3.2. Features common to the E3 and DH models

3.2.1. Household behavior

While the E3 model considers a single representative household, DH distinguishes five. In both models, the structure of the household utility maximization problem matches the structure described in Section 2. This structure allows climate policy to affect household behavior along several important dimensions: labor-leisure choice, the choice between current and future consumption, and the allocation of expenditures across goods and services at each point in time.

Fig. 1 displays the nested consumption structure. At the lowest nest, the representative household uses a CES function to aggregate domestically and foreign supplied goods from producers. At the next level of the nest, a Leontief aggregation function is used to add transportation and trade costs (provided by domestic transportation and trade industries) to the final cost of the consumption good. At the top level of the nest, an aggregation function combines the consumption of each good into the composite consumption good.

3.2.2. Functional forms and first-order conditions

In addition to having a common utility function structure, both models employ the same functional forms. A constant-elasticity-of-substitution functional form represents substitutability of consumption across time. With this functional form, Eq. (1) translates to

$$U_0 = \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\sigma} \left(C_t^q\right)^{1-\sigma} \tag{20}$$

where q indicates the household (or quintile), β is the discount factor, and $1/\sigma$ is the intertemporal elasticity of substitution. These parameters are assumed to be equal across all DH model households and match the values for the E3 household. Using a CES functional form, full consumption is

$$C_t^q = \left[\left(\overline{C}_t^q\right)^{\frac{\eta^q-1}{\eta^q}} + \left(\alpha_\ell^q\right)^{\frac{1}{\eta^q}}\left(\ell_t^q\right)^{\frac{\eta^q-1}{\eta^q}}\right]^{\frac{\eta^q}{\eta^q-1}} \tag{21}$$

where η^q is the elasticity of substitution between goods and leisure, and α_ℓ^q is the leisure intensity parameter. In the DH model, these parameters are calibrated to match data on consumption and leisure for different household groups, and they generally vary across households. In general, they also differ from the values for the representative household in E3. (See Section 4 for further discussion.)

The first-order conditions for each household are

$$\frac{\partial L^q}{\partial \overline{C}_t^q} \quad : \quad \left[\left(\overline{C}_t^q\right)^{\frac{\eta^q-1}{\eta^q}} + \left(\alpha_\ell^q\right)^{\frac{1}{\eta^q}}\left(\ell_t^q\right)^{\frac{\eta^q-1}{\eta^q}}\right]^{\frac{1-\sigma\eta^q}{(\eta^q-1)}} \left(\overline{C}_t^q\right)^{\frac{-1}{\eta^q}} = \lambda_t^q \overline{p}_t^q \tag{22}$$

$$\frac{\partial L^q}{\partial \ell_t^q} \quad : \quad \left[\left(\overline{C}_t^q\right)^{\frac{\eta^q-1}{\eta^q}} + \left(\alpha_\ell^q\right)^{\frac{1}{\eta^q}}\left(\ell_t^q\right)^{\frac{\eta^q-1}{\eta^q}}\right]^{\frac{1-\sigma\eta^q}{(\eta^q-1)}} \left(\alpha_\ell^q\right)^{\frac{1}{\eta^q}}\left(\ell_t^q\right)^{\frac{-1}{\eta^q}} = \lambda_t^q \overline{w}_t \tag{23}$$

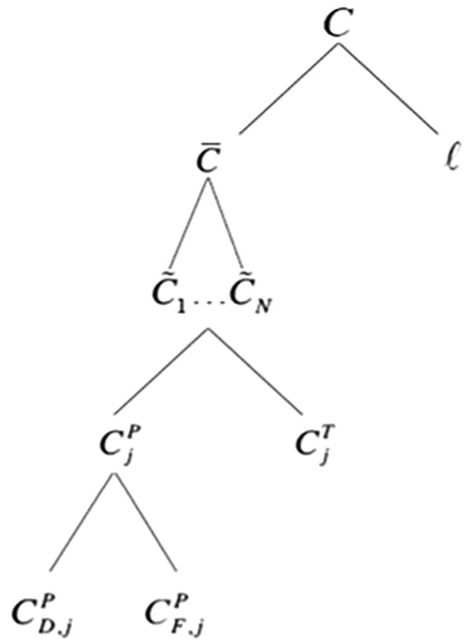


Fig. 1. Nested consumption structure.

$$\frac{\partial L^q}{\partial W^q_{t+1}} \quad : \quad \lambda^q_t = \beta(1+\overline{r}_{t+1})\lambda^q_{t+1} \tag{24}$$

These first-order conditions determine each household's allocation of expenditure between the consumption composite and leisure, given $\overline{w}$ and the composite price $\overline{p}$. The price $\overline{p}$, in turn, depends on the composition of the bundle of consumer goods that make it up. Because consumption bundles differ, the unit price for the consumption of goods and services generally differs across households.

3.2.3. Prices, budget constraints, and tax payments

In the numerical models, households have Cobb-Douglas preferences over consumption goods and services with constant expenditure share parameters $\alpha_j^{C,q}$. The price of the aggregate consumption good for each household is given by

$$\overline{p}^q_t = \prod_{j=1}^{N_c} \tilde{p}_{j,\ t}^{\alpha_j^{C,q}} \tag{25}$$

where $\tilde{p}_{j,\ t}$ denotes the price of consumer good or service j at time t, as determined by the E3 model, inclusive of any commodity taxes and net of any subsidies. All households face the same after-tax or subsidy prices. However, the five representative households in DH have different expenditure shares $\alpha_j^{C,q}$; hence the composite price $\overline{p}^q_t$ in the first-order equations differs across households.

In Section 2's analytical model, households received endowments only of time and capital. In the DH and E3 models, we also include endowments of transfer income (held fixed in real terms across policies), a lump-sum component of taxes, and (in some policy cases) lump-sum rebates. In the numerical models, the household faces an intertemporal budget (wealth) constraint. The equation of motion for household wealth is

$$W^q_{t+1} - W^q_t = \overline{w}_t \overline{l}^q_t + \overline{r}_t W^q_t + G^q_t + LS^q_t - T^q_t - \overline{p}^q_t \overline{C}^q_t - \overline{w}_t \ell^q_t \tag{26}$$

where G, LS, and T refer to nominal levels of government transfer income, lump-sum rebates (if any), and lump-sum taxes, respectively.

The returns on labor and capital, $\overline{w}_t$ and $\overline{r}_t$, are from the E3 model. We specify them as the same across households in both the reference and policy cases.[19] Total transfers from the E3 model are allocated across the five representative households according to their shares in data described below from the Survey of Consumer Finances. This applies in both the reference and policy cases. Consequently, under a carbon tax policy, the percentage change in household transfer income is the same across households. In most policy scenarios, we specify equal allocations of lump-sum transfers across households, but in Section 8 we consider policies involving differing allocations designed to achieve certain distributional objectives.

The cuts in marginal tax rates or total lump-sum rebates needed for revenue neutrality are determined by E3. We apply the same marginal tax cuts in percentage terms to each of the separate household groups in the DH model. In simulations with recycling via lump-sum rebates, each representative household receives an equal share of the overall rebate from E3 in each period.

Because the DH model's households respond to policy changes, their tax payments are endogenous. To check the consistency between the DH and E3 models, we aggregate these tax payments and compare them with the payments from E3. We find that these payments nearly perfectly aggregate to the levels from E3, never differing by more than 0.9%. This close correspondence reflects the consistent aggregation in the initial allocation of endowments, income sources, and expenditures in the DH model. The next section describes the relevant procedures.

4. Data and parameters

4.1. Data sources

Here we briefly describe the data sources and the ways they are organized in the complete dataset. We also describe the steps we make to achieve consistency between the E3 and DH models. Details are provided in Appendix A.

For the DH model, we obtain data on before-tax income from the 2013 Survey of Consumer Finances (SCF). These data indicate before-tax household income by source (labor, capital, and transfer income) for a representative sample of 6015 households. The data appendix offers details on the elements of each source of income.

We derive household after-tax incomes by applying, to the SCF before-tax data, federal- and state-level tax information from the National Bureau of Economic Research's TAXSIM model (Feenberg and Coutts, 1993).[20] The TAXSIM data do not break down tax liabilities by income source. To provide this breakdown, we calculate for each household the share of before-tax income from each source and multiply each share by the total tax liability.

We obtain household expenditures on each consumer good using the 2013 Consumer Expenditure Survey (CEX) microdata collected by the US Department of Labor's Bureau of Labor Statistics (BLS). The CEX provides data on expenditures, income, and demographic characteristics of representative consumers in the United States.

These data are collected through two surveys: the Interview Survey and Diary Survey. The Interview Survey focuses on large consumer goods, such as spending on housing, vehicles, and health care. The Diary Survey collects data on weekly expenditures of different households that are followed for only two weeks. To account for a complete listing of expenditures for each household, we combine data from the two surveys. Appendix A offers details.

We combine the SCF income data and CEX expenditure data in a way that ensures that for each quintile, household expenditure is consistent

[19] We assume that Harrod-neutral (labor-augmenting) technological progress applies uniformly across all household groups. Hence the relative returns to labor across households do not change over time.

[20] The SCF does not provide state of residence. We randomly assign each household to a state based on population weights to determine state tax liabilities.

Table 3
Average after-tax income shares by source by quintile.

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Labor	53%	71%	76%	80%	50%
Capital	9%	8%	12%	13%	47%
Transfer	38%	21%	12%	6%	3%
Total	100%	100%	100%	100%	100%

with income and saving. As described in the appendix, this involves matching expenditure data from the CEX to each SCF household and using CEX data to calculate household saving for each household quintile.

When defining quintiles, we rank households both by expenditure and by income. In this study, we focus on results by expenditure quintiles, but we also display (in Section 7) some results when quintiles are defined in terms of income.

Table 3 shows the average after-tax income by source by quintile, and Table 4 shows the average expenditure shares by good by quintile, when quintiles are defined in terms of their total expenditure.

4.2. Achieving consistency in aggregation

We adjust the data so that the benchmark outcome of the DH model, when aggregated across households, matches the outcome of the more aggregated E3 model. Specifically, we impose the requirement that aggregate after-tax income from each source, aggregate consumption of each good, and aggregate savings match across models in the benchmark dataset. Using the merged SCF-CEX dataset, we calculate quintile shares of income source, consumption good, and savings. For each quintile in the DH model, the level of after-tax income, consumption, and savings is equal to the quintile share times the E3 level of after-tax income, consumption, and savings.

4.3. Parameters

Here we briefly describe the household utility parameters for the two models.[21] In E3, the discount factor β is calibrated to be consistent with a long-run interest rate of 4%. We use a value of 2 for σ, which implies an intertemporal elasticity of substitution in consumption ($1/\sigma$) of 0.5, a value between time-series estimates (Hall, 1988) and cross-sectional studies (Lawrance, 1991). We apply the same values to the DH households.

In the E3 model, the compensated elasticity of labor supply and the nonlabor income elasticity are functions of the consumption-leisure ratio, the price of consumption — after-tax wage ratio, the elasticity of substitution between consumption and leisure, η, and the fraction of time spent working. Conditional on our data for prices, consumption, and labor supply, we set the values of (a) the consumption-leisure elasticity of substitution and (b) the fraction of time spent working to 0.773 and 0.66, respectively, so the compensated elasticity of labor supply is 0.3 and the nonlabor income elasticity is 0.25.[22] In the DH model, we assume each household spends the same fraction of time working. Given the differences in consumption-leisure ratios, we recalibrate η^q, the consumption-leisure elasticity for each quintile q, so that each household has the same compensated elasticity of labor supply and nonlabor income elasticity as in the E3 model. Expenditure shares $\alpha_j^{C,q}$ are derived from our SCF-CEX household data set.

[21] Details are provided in Goulder and Hafstead (2017).

[22] The compensated elasticity if labor supply is at the high end of estimates for married men and single women (0.1–0.3) and in the middle range of estimates for married women (0.2–0.4). McClelland and Mok (2012) provide a review of recent labor supply estimates.

Table 4
Average expenditure shares by good by quintile.

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Motor vehicles	2.2%	3.5%	5.5%	5.6%	5.2%
Furnishings and household Equipment	2.2%	2.5%	3.0%	3.2%	4.0%
Recreation	7.3%	7.9%	7.9%	8.4%	9.7%
Clothing	4.1%	3.7%	3.5%	3.8%	3.9%
Health care	23.3%	22.8%	20.0%	21.5%	19.5%
Education	0.6%	0.8%	1.8%	2.3%	2.7%
Communication	2.4%	2.7%	3.0%	2.9%	2.3%
Food	8.7%	8.6%	7.9%	7.1%	5.8%
Alcohol	0.9%	1.5%	1.3%	1.2%	1.2%
Motor vehicle fuels (and lubricants and fluids)	3.9%	4.5%	4.7%	4.4%	3.4%
Fuel oil and other fuels	0.3%	0.2%	0.2%	0.2%	0.3%
Personal care	2.0%	2.1%	2.2%	2.2%	2.2%
Tobacco	3.1%	2.8%	1.9%	1.2%	0.7%
Housing	26.4%	20.8%	19.0%	14.8%	12.5%
Water and waste	1.6%	1.6%	1.6%	1.5%	1.3%
Electricity	2.4%	2.0%	1.9%	1.6%	1.3%
Natural gas	0.5%	0.5%	0.5%	0.5%	0.5%
Public ground	0.4%	0.4%	0.3%	0.3%	0.4%
Air transportation	0.1%	0.2%	0.4%	0.5%	0.8%
Water transportation	0.0%	0.0%	0.0%	0.0%	0.0%
Food services and accommodations	1.7%	3.0%	4.2%	6.0%	8.1%
Financial services and insurance	3.5%	5.1%	5.8%	6.8%	8.0%
Other services	2.3%	2.6%	3.2%	3.9%	5.7%
Net foreign travel	0.1%	0.2%	0.3%	0.3%	0.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

5. The reference case path and carbon tax

5.1. The reference case

With the data described in the previous section, the E3 model would generate a balanced growth path. In particular, the ratio of CO_2 emissions to GDP would be constant along that path. Such a time-path would not be consistent with business-as-usual projections from a range of leading private and government studies. To generate a more plausible reference (business-as-usual) time-path of emissions, we specify a time-profile for energy-augmenting technological change. This time-profile gives rise to a reference case path with a slowly declining energy intensity of production that approximates the business-as-usual forecast offered by the Energy Information Administration's *Annual Energy Outlook* 2016 (AEO; EIA, 2016).[23]

5.2. Carbon tax design

We consider a tax with the following features[24]:

Time Profile: The tax starts at $40 per metric ton in 2013$ in 2020 after a three-year phase-in. In 2018 and 2019, the tax is $13.33 and $26.67, respectively. After 2020, the tax increases in real terms at a rate of 2% annually. The tax is held constant in real terms after 2050. Fig. 2 displays the time profile of the carbon tax.

Coverage: The tax covers all direct purchases of primary fossil fuels and imports of refined products such as gasoline, diesel, and heating

[23] We focus on matching AEO (2016) forecasts for economic growth, fossil fuel prices, electric generation shares, and total emissions. See Goulder and Hafstead (2017) for a complete description of the reference case calibration procedure. Chen et al. (2018) describe the sensitivity of future emissions to alternative baseline forecasts.

[24] The price path we apply has some similarities to the one in the proposed Whitehouse-Schatz American Opportunity Carbon Fee Act, which calls for a price starting at $49 (in 2018$) in 2018 and rising at 2% above inflation.

oil. This specification covers 99.9% of all domestic emissions from the combustion of fossil fuels.

Point of Regulation: The tax is imposed midstream — that is, at the industrial user's gate and the port of entry for imports of refined products. It is based on the carbon content of the fuel purchased, and it covers emissions from both industrial combustion of the product and combustion of any downstream products. Relative to the case where the points of regulation are upstream (at the wellhead or mine mouth), midstream implementation allows for alternative specifications of the sectoral coverage of the policy.

Revenue Recycling: We consider four revenue-neutral uses of carbon revenue: (1) lump-sum rebates, (2) payroll tax cuts, (3) individual income tax cuts, and (4) corporate income tax cuts. The revenue returned to the private sector is equal to the net revenue yield of the carbon tax, where the latter is the gross carbon tax revenue adjusted for any revenue impacts of policy-induced changes in the tax base of other taxes and expenditure impacts of policy-induced changes in the price of government purchases or nominal values of transfers.[25]

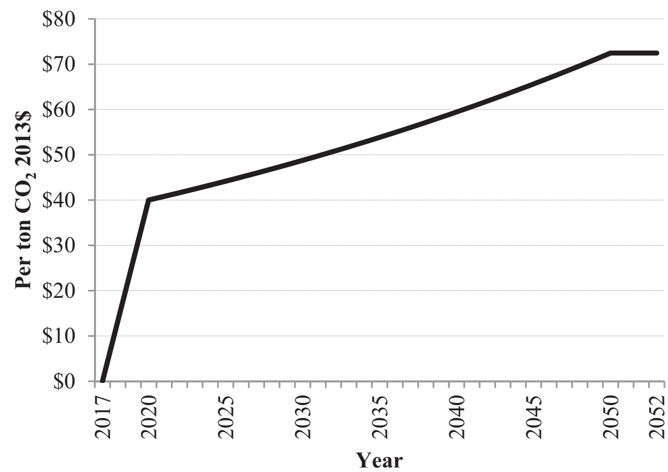


Fig. 2. Time profile of carbon tax, 2017–2050.

6. Aggregate impacts of the carbon tax

Here we focus on aggregate (economy-wide) impacts of the carbon tax under alternative recycling scenarios, displaying its impacts on emissions, prices, factor returns, GDP, and (according to the equivalent variation) welfare.

Fig. 3 displays CO_2 emissions in the reference case and under the carbon tax, when revenues are recycled through lump-sum tax cuts.[26] The tax reduces emissions by 17 and 30% in 2020 and 2035, respectively. Over the interval 2017–2050, 64–68% of annual reductions are due to reductions in emissions from the power sector, reflecting electric utilities' substitution away from coal-fired generation and toward natural gas generation and non-fossil-based generation.

In 2020, following the 3-year phase-in of the tax, gross revenues in 2013$ are projected to be $164 billion. The increasing tax rate prevents revenues from falling, despite declining emissions: revenues are projected to be $179 billion (again in 2013$). As mentioned above, in all policy simulations government spending and transfers are maintained at reference-case levels in real terms. What is recycled through rebates or tax cuts is the carbon tax revenue net of any additional revenue needed to maintain real government expenditure or transfers. In 2020, approximately 50% of the gross carbon tax revenue is available for recycling. This fraction falls over time as the capital stock shifts from more profitable industries (such as extraction) to less profitable industries (such as services).

Tables 5–7 indicate the carbon tax's impacts on prices of inputs, consumer goods, and returns to factors.[27] Table 5 shows the percentage change in producer good prices relative to the reference case, for years 2020, 2035, and 2050. As expected, the price impacts are largest in the industries with the greatest carbon intensities (coal-fired and other fossil electricity generation, petroleum refining, and electricity transmission and distribution).[28] The reduction in the prices of coal and natural gas reflect the backward shifting of the burden of the tax, which is imposed on the purchasers of these fuels (e.g., coal-fired electricity generators and natural gas distributors).[29] This reduces the demands for coal and natural gas, which results in a decrease in the producer prices of coal and natural gas in those two extractive industries. The higher relative prices of carbon-intensive inputs motivate producers to substitute away from these inputs, and such substitution represents a channel through which emissions reductions are achieved.

Tables 6 and 7 show the policy-induced percentage changes in consumer good prices and in returns to factors. A household that relies disproportionately on consumer goods with relatively large percentage increases in prices will experience a larger adverse use-side impact than other households. Similarly, a household that relies disproportionately on a source of income with a relatively large increase in that factor's return will experience a larger positive source-side impact.

As discussed in Section 2, by affecting the absolute changes in prices, the choice of numeraire good also affects the calculated percentage changes. However, the numeraire choice does not affect the rankings of these percentage changes. Thus, irrespective of the numeraire choice, the percentage changes shown in Tables 6 and 7 convey which goods and factor returns have the largest relative price changes.

Table 6 reveals that the carbon tax causes the largest relative price increases for motor vehicle fuels, fuel oils, electricity, and natural gas. This squares with the high carbon intensities shown in Table 2 for these goods and services. Thus the adverse use-side impacts will be disproportionately large for households with higher expenditure shares for these goods. We address the expenditure-share differences in the next section's assessment of distributional impacts.

Table 7 shows the carbon tax's impact on the after-tax returns to labor, capital, and transfer endowments — the impacts that underlie the source-side effects.[30] The table displays the change in these returns across the four recycling options, for years 2020, 2035, and 2050. Three key results emerge from the table. First, in the shorter term (up to 2020), the return to capital falls relative to the return to labor under every form of recycling except corporate tax recycling. Capital goods are relatively carbon-intensive in their production. As a result, much of the burden of a carbon tax falls on capital. As indicated below, this exerts a progressive source-side effect, since capital's share of total income increases as one moves from lower to higher income quintiles. The specific form of recycling influences the extent to which the return to capital falls — or even whether it falls at all. The decline in capital's return

[25] By affecting incomes, the carbon tax alters the tax base of income and payroll taxes. It can also indirectly alter revenues from sales and other commodity taxes to the extent that it affects patterns of consumer spending. We hold fixed the provision of government services, but allow the government to shift its purchases across different variable inputs (producer goods and labor) in response to relative price changes. Increases in transfers resulting from price changes reduce the amount of revenue that can be returned to households.

[26] Emissions reductions are similar under the other forms of recycling.

[27] As indicated in Section 2, these prices reflect the choice of "financial services and insurance" as numeraire.

[28] The adjustment costs imply imperfect capital mobility, which prevents producers from passing forward to consumers all of the policy-induced increases in production costs. The fraction of the policy costs borne by producers declines with time as firms move capital stocks and output levels closer to desired long-run levels.

[29] We assume a given ratio of the world price of oil to the price index for a fixed basket of imported goods. As a result, the changes in the price of oil in Table 5 reflect changes in the price of this basket of goods.

[30] All figures in the table are in nominal terms, in keeping with the definition in Section 2 of the source-side impact.

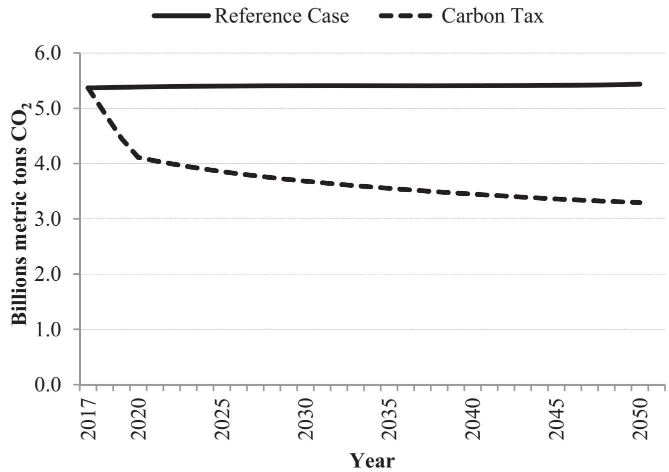


Fig. 3. Economy-wide carbon dioxide emissions, 2017–2050.

relative to labor's is greatest when recycling is via lump-sum rebates. In that case, recycling does not involve any reduction in individual or corporate income tax rates. In contrast, the return to capital rises relative to the return to labor under corporate tax recycling, reflecting the focused reduction in corporate income tax rates in this case. In this case, the adverse impact on capital returns associated with the higher carbon intensity of capital goods is fully offset by the positive impact from corporate income tax recycling.

Second, over time the adverse impact on the return to capital tends to diminish. This is in keeping with the carbon tax's adverse impact on investment. In the longer term, the lower capital intensity of the economy implies higher returns to capital than in the short term.

Third, in all cases, the carbon tax implies higher nominal transfers. Our simulations assume that transfers are indexed to the consumer price index (CPI). Hence the carbon tax prompts changes in nominal transfers in proportion to the policy-induced change in the CPI. Generally, the carbon tax raises the CPI, and thus the carbon tax implies an increase in nominal transfers. As we will see in the next section, this positive source-side impact is especially important for low-income households, for whom transfers represent an especially large share of income. Previous studies have pointed out that changes in nominal

Table 5
Impacts on producer prices (percentage changes from reference case values).

Industry	2020	2035	2050
Oil extraction	0.7	1.9	2.4
Natural gas extraction	−13.6	−0.1	0.1
Coal mining	−16.8	−2.5	0.4
Electric transmission and distribution	10.1	14.9	16.1
Coal-fired electricity generation	40.2	75.4	106.6
Other fossil electricity generation	21.6	31.8	41.0
Non-fossil electricity generation	17.7	6.6	3.0
Natural gas distribution	5.9	15.2	20.3
Petroleum refining	13.0	16.5	19.7
Pipeline transportation	0.3	3.6	4.6
Mining support activities	0.4	1.8	2.1
Other mining	−0.8	0.4	0.5
Farms, forestry, fishing	0.4	1.3	1.5
Water utilities	0.3	0.4	0.6
Construction	0.4	0.7	0.8
Wood products	0.2	0.8	0.9
Nonmetallic mineral products	0.2	1.1	1.3
Primary metals	1.1	2.3	2.5
Fabricated metal products	0.1	0.7	0.8
Machinery and misc. manufacturing	−0.4	0.3	0.3
Motor vehicles	−0.1	0.5	0.5
Food and beverage	0.3	0.9	1.0
Textile, apparel, leather	0.1	0.4	0.5
Paper and printing	0.3	1.0	1.1
Chemicals, plastics, and rubber	1.1	2.6	2.9
Trade	−0.1	0.1	0.1
Air transportation	2.0	3.1	3.6
Railroad transportation	−1.5	0.4	0.9
Water transportation	1.8	2.7	3.1
Truck transportation	1.9	2.6	2.8
Transit and ground passenger transportation	1.1	1.3	1.4
Other transportation and warehousing	0.4	0.8	0.8
Communication and information	−0.2	−0.1	0.0
Services	0.0	0.0	0.0
Real estate and owner-occupied housing	0.3	0.4	0.6
All industries (Producer Price Index)	0.8	1.6	2.0

Table 6
Impacts on consumer good prices (percentage changes from reference case values[a]).

Consumption category	2020	2035	2050
Motor vehicles	0.0	0.2	0.2
Furnishings and household equipment	0.0	0.4	0.4
Recreation	−0.1	0.1	0.1
Clothing	−0.1	0.2	0.1
Health care	0.0	0.1	0.2
Education	0.0	−0.1	−0.1
Communication	−0.2	−0.1	0.0
Food	0.2	0.6	0.7
Alcohol	0.2	0.5	0.6
Motor vehicle fuels (and lubricants and fluids)	7.5	10.2	12.8
Fuel oil and other fuels	7.4	10.0	12.5
Personal care	0.1	0.3	0.4
Tobacco	0.3	0.6	0.8
Housing	0.3	0.4	0.6
Water and waste	0.2	0.3	0.5
Electricity	9.7	14.3	15.4
Natural gas	5.6	14.5	19.3
Public ground	0.9	1.2	1.3
Air transportation	1.2	2.0	2.2
Water transportation	1.3	2.0	2.3
Food services and accommodations	0.0	0.0	0.0
Financial services and insurance	0.0	0.0	0.0
Other services	0.0	0.0	0.0
Net foreign travel	1.5	2.4	2.7
All consumer goods (Consumer Price Index)	0.6	1.0	1.2

[a] The category financial services and insurance is the numeraire.

Table 7
Impacts on factor prices and transfers (percentage changes from reference case values).

	After-tax wage	After-tax interest rate	Transfers
Lump-sum rebates			
2020	−0.2	−2.2	0.6
2035	−0.5	−1.0	1.0
2050	−0.7	−0.4	1.2
Payroll tax cuts			
2020	0.7	−1.8	0.6
2035	0.4	−0.9	1.0
2050	0.2	−0.4	1.2
Individual income tax cuts			
2020	0.4	−1.2	0.5
2035	0.3	−0.5	0.9
2050	0.1	−0.2	1.1
Corporate income tax cuts			
2020	−0.1	0.4	0.5
2035	0.1	0.1	0.7
2050	0.1	0.0	0.8

transfers can significantly influence the source-side impacts of a carbon tax.[31] In the next section, we assess the implications of transfer indexing by comparing our central case outcomes with the results from a counterfactual simulation in which transfers are fixed in nominal terms.

Table 8 shows the GDP and aggregate welfare impacts of the carbon tax in the E3 model under the four forms of recycling. The GDP and welfare costs are greatest under lump-sum recycling. This form of recycling does not involve any cuts in marginal rates and thus does not reap the potential efficiency gains from rate reductions. In contrast, the GDP costs and aggregate welfare costs are lowest under corporate income tax recycling. This reflects the fact that in the model, the corporate income tax is more distortionary (that is, has a higher marginal excess burden) than the individual income tax and payroll tax. Accordingly, recycling through cuts in corporate income tax rates confers the largest benefit and thereby reduces GDP and welfare costs the most.[32]

7. Distributional impacts in the absence of targeted compensation

Here we examine the impacts across the five representative household groups. As mentioned in Section 4, the households are grouped and ranked by total expenditure.[33] When aggregated, the results from the DH model conform closely to the more aggregated outcomes of the E3 model.[34]

7.1. Use- and source-side impacts

7.1.1. Choice of numeraire

As indicated in Section 2, in this analysis the overall welfare impacts applying to each household group are expressed as the equivalent variation relative to the household's reference case wealth. As noted in that section, the choice of numeraire does not alter the overall welfare impact from any given carbon tax policy.

However, as noted, the choice of numeraire is significant because it affects, for any given household, the relative size of the use- and source-side impacts. Although it is possible to choose any good as numeraire, some choices have a stronger empirical basis than others. To illustrate it is possible to choose as numeraire the most carbon-intensive good. However, with this numeraire, the carbon tax would have no impact on the price of that good (it would remain 1) and instead the tax would cause prices of most or all other produced goods to fall. This is both implausible and inconsistent with usual monetary policy.[35]

Our preferred numeraire is one according to which the carbon tax yields an increase in the nominal price of each consumer good or service in proportion to its direct and indirect carbon content. In keeping with this objective, we have employed as numeraire the good whose direct and indirect carbon content is approximately zero. As indicated in Table 2, this good is financial services and insurance. With this numeraire, the carbon tax has virtually no impact on the price of this good, while other consumer goods increase in price according to their direct and indirect carbon content — that is, according to the increase in cost associated with the carbon tax. This is consistent with a monetary policy that aims for a steady rate of inflation, and in which departures from this rate reflect added costs from policy shocks. We consider the implications of alternative numeraires in Appendix B.

7.1.2. Use-side impacts

Figs. 4–5 display the use-side and source-side welfare impacts, respectively, from the carbon tax in our central case. The figures show the impacts over the time intervals 2018–2020 and 2018–2040, as well as over the interval of infinite length that begins in 2018. Appendix C offers a similar set of figures with the impacts displayed for the years 2020, 2030, and 2050. Impacts are expressed as a percentage of reference case wealth. In the recycling cases involving tax cuts, we assume that the rate cuts are the same for all quintiles. In the cases involving lump-sum rebates, each quintile receives one-fifth of the total rebate provided in each period. (Later, we consider alternative rebate schemes aimed at achieving certain distributional objectives.)

For the use-side results in Fig. 4, the two columns calculate the impacts two ways. In the left-hand column, the use-side impact accounts for the policy-induced changes in the prices of goods and services but excludes the impact on the price of leisure (another "good" that a household can "purchase" by working less and sacrificing income). The right-hand column offers results from our broader measure, which accounts for policy-induced changes in the price of leisure.

The figure illustrates four key results. First, under each of the recycling options, the use-side impact is regressive: the welfare impact is more negative the lower the expenditure rank of the quintile. This reflects the fact that lower-quintile households spend a larger share of their incomes on carbon-intensive goods and services than do higher-quintile households. The outcome is regressive regardless of whether changes in the price of leisure are ignored (left-hand column) or considered (right-hand column).[36]

Second, for all quintiles, the magnitude of the use-side impact increases with the length of the time-interval considered. This is in

[31] See, for example, Fullerton et al. (2011) and Cronin et al. (2017).

[32] These results can be sensitive to model structure and the vintage of the data used. The estimated excess burden of the corporate tax reflects particular assumptions about how firms finance their investments. Alternative assumptions could lead to different results. Also, the results in the table are based on 2013 data, which included a statutory federal corporate income tax rate of 35%. The Tax Cuts and Jobs Act of 2017 reduced this rate to 21%. Recent work by Chen and Hafstead (2019) indicates that, consistent with theory, the tax reform reduces the marginal excess burden of the corporate income tax and thereby reduces the efficiency benefit from recycling carbon tax revenues via (further) cuts in the corporate tax rate. This work indicates that, after the Tax Cuts and Jobs Act, cutting the corporate income tax remains the most cost-effective form of recycling among the ones we consider.

[33] Expenditure more closely correlates with lifetime income than with income from a single year.

[34] The reference case and policy case outcomes from the DH model do not perfectly aggregate to those in the single-household E3 model. But the differences are very small, in keeping with the perfect aggregation that we impose on the benchmark data. Under all recycling options, the difference between the sum of the equivalent variation welfare impacts summed across quintiles and the equivalent variation for the E3 model's representative consumer is never above 3%.

[35] We are grateful to Gib Metcalf, Don Fullerton, and Rob Williams for pointing out to us the significance of the numeraire choice to the estimated relative size of the use- and source-side impacts. Williams et al. (2015) provide an insightful discussion of related issues. Rausch et al. (2011) offer an alternative method for examining the distributional implications of the use- and source-side price changes, an approach in which numeraire choice does not affect the results. Below, we briefly present and evaluate results from the application of this alternative approach.

[36] Earlier studies also have tended to obtain regressive use-side impacts, although those studies did not include attention to the influence of changes in the price of leisure. Nor did they consider how the impacts change over time.

Table 8
GDP and welfare costs of a carbon tax under alternative recycling options.

	Recycling method			
	Lump-sum rebates	Cuts in employee payroll taxes	Cuts in individual income taxes	Cuts in corporate income taxes
GDP costs[a]				
- as pct. of reference GDP	0.28%	0.13%	0.16%	0.19%
- per ton of CO_2 reduced[b]	$54.67	$26.41	$31.25	$38.38
Welfare costs[c]	$2563.44	$2046.83	$1684.82	$380.99
- as pct. of wealth	0.43%	0.34%	0.28%	0.06%
- per dollar of gross revenue	$0.39	$0.31	$0.26	$0.06
- per ton of CO_2 reduced	$46.97	$37.63	$31.08	$7.25

[a] GDP costs measured as present value of real GDP loss 2016–2050, using 3% real interest rate.
[b] Present value of cumulative tons reduced, using 3% real interest rate.
[c] Welfare costs are the negative of the equivalent variation, expressed in billion 2013$.

keeping with the increasing size of the carbon tax and the associated increases in the scale of the price impacts.

Third, the magnitude of the use-side welfare impact over any time-interval depends on the type of recycling. The impacts are smallest when recycling is via cuts in the corporate income tax. This is in keeping with the fact that the corporate tax induces households to save more and consume less, which implies smaller increases in consumer good prices.

Fourth, when recycling takes the form of payroll tax cuts or individual income tax cuts, the use-side impacts are larger when changes in the price of leisure are accounted for: effects in the right-hand column are larger than those in the left-hand column. Each of these two forms of recycling involves cuts in the tax on wages. This raises the after-tax wage, which is also the price of leisure. Accounting for the increased price of leisure enlarges the use-side effect.

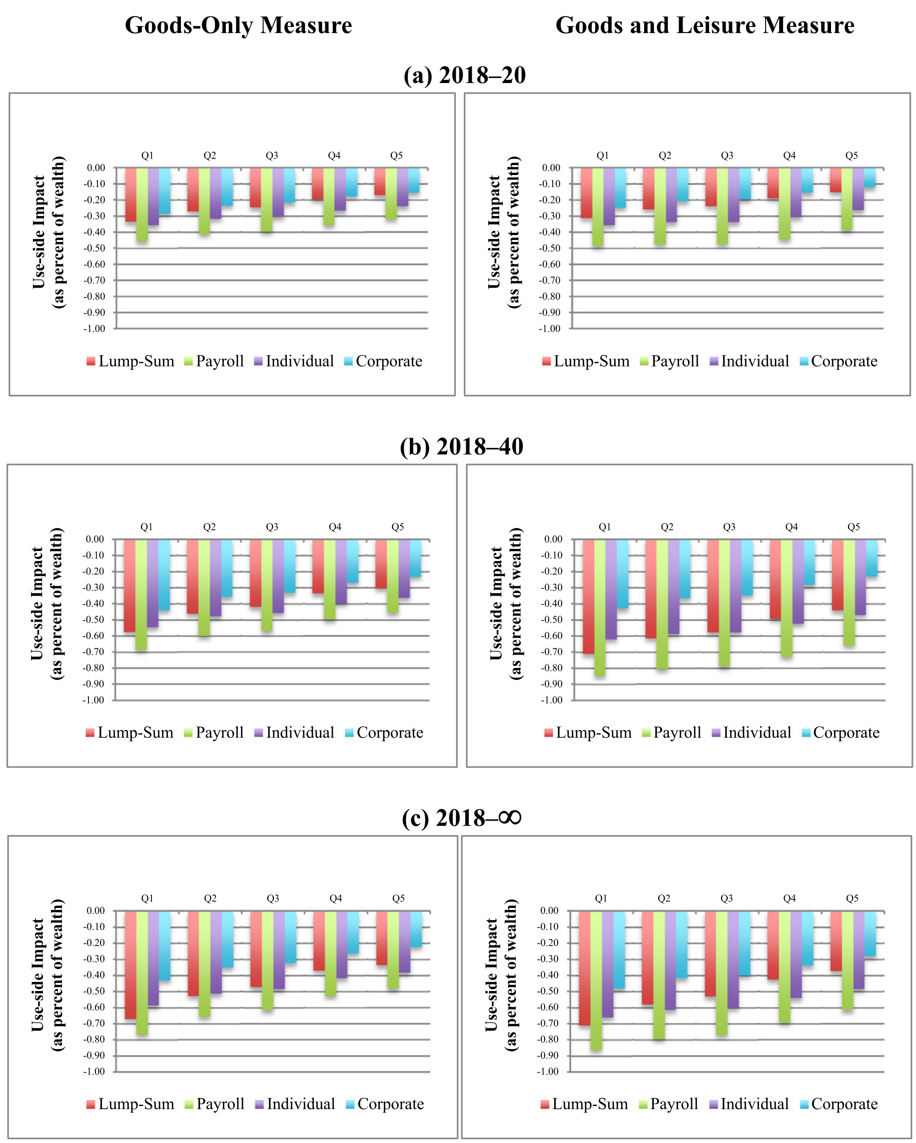


Fig. 4. Use-side impacts over time intervals, by quintile.

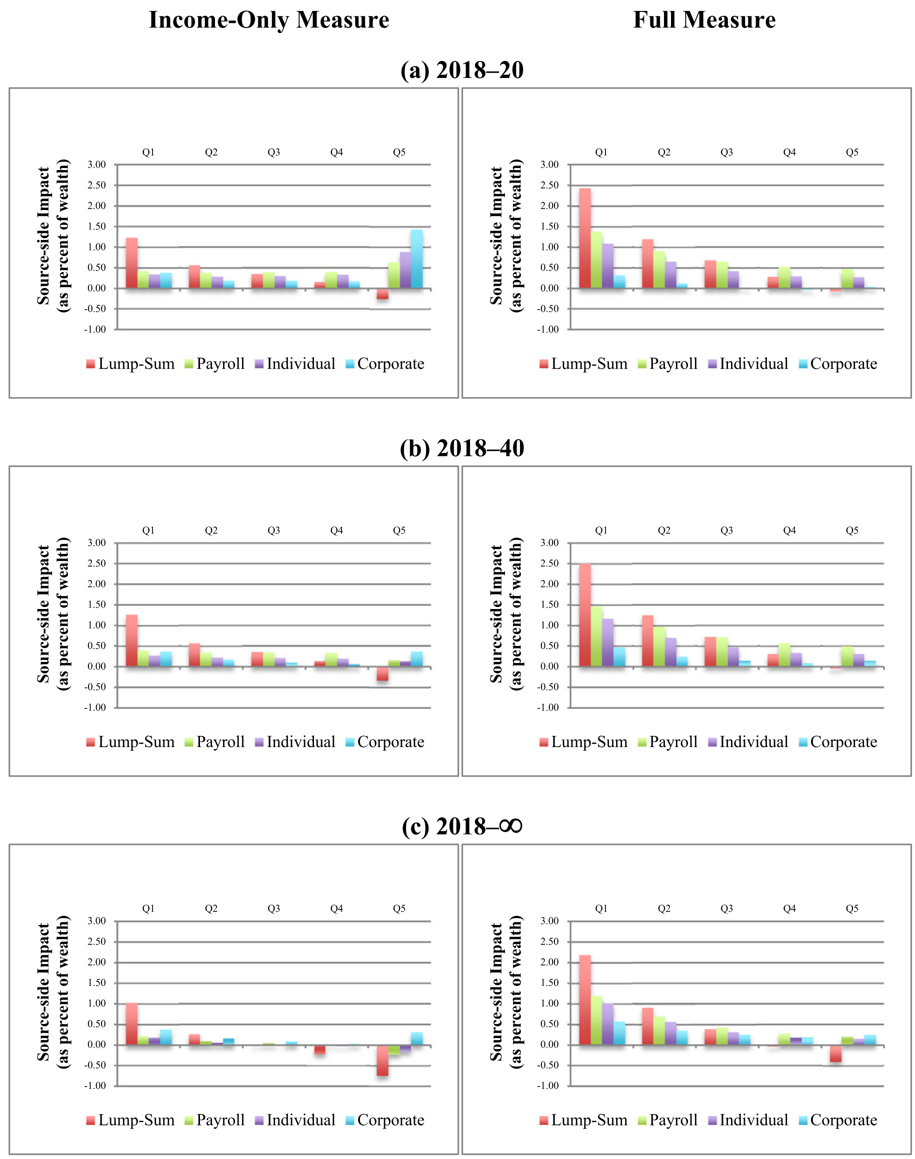


Fig. 5. Source-side impacts over time intervals, by quintile.

7.1.3. Source-side impacts

Fig. 5's source-side impacts are the welfare consequences of policy-induced changes in the values of sources of income or leisure, measured in nominal terms, holding nominal prices of goods and services at reference-case levels. Again we examine the impacts over specified intervals of time and under the four forms of revenue recycling considered previously.

The left-hand column shows results based on the narrower, typical "income-only" measure of the source-side impact, one that considers only the policy's effects on after-tax labor income, after-tax capital income, and transfer income. The right-hand column offers a broader measure that considers the policy's impact on each household's overall endowment of labor — the sum of the value of labor supplied and the value of the household's nonlabor (leisure) time. The broader measure can offer a more accurate assessment of the welfare consequences of changes in labor supply. When a household works less, its labor income is reduced. A welfare measure that considers only this loss of income would overstate the welfare loss associated with this change, since the value of the increase in nonwork (leisure) time compensates to an extent for the reduction in income. Our broader measure accounts for this offset.[37]

The key messages from Fig. 5 are as follows. (These are also the key messages from the corresponding figure in Appendix C, which displays results for particular years.) First, in almost every case, the source-side impacts are positive, in contrast with the impacts on the use side. One factor behind the positive welfare impacts is revenue recycling. Each form of recycling contributes to nominal income: the lump-sum rebates do so directly, while the cuts in the marginal rates of payroll, individual income, or corporate income taxes do so by increasing the after-tax returns to factors. Changes in nominal transfers are another key factor

[37] The broader measure also accounts for the impact of policy on each household's savings in a given period or during the time interval of focus. Any increase (decrease) in saving implies greater (lower) potential for future consumption and utility. Although some of this change in future consumption can occur beyond the period or time interval of focus, the source of this change is in the period or during the interval of focus; hence it can be attributed to those points in time. Accounting for the savings impact also has the virtue of enabling the sum of the source- and use-side impacts to perfectly match the overall welfare impact, as measured by the equivalent variation for the period or interval in question.

behind the positive source-side impacts. As mentioned, our simulations assume that government transfers are kept constant in real terms. Because the carbon tax raises overall prices to consumers, nominal transfers must be higher under the carbon tax than in the reference case to maintain their real value. This is especially important for low-income households, for which transfers constitute a large share of overall income.

Second, the source-side impacts are generally progressive — with some exceptions under corporate income tax recycling. Contributing to the progressivity is the fact that, as indicated in Table 7, the carbon tax reduces after-tax returns to capital more than returns to labor, reflecting that fact that capital-labor ratios of carbon-intensive goods and services tend to be higher than the average ratios for the economy. Consequently the carbon tax reduces demands for capital relative to labor and lowers capital's relative return. Because higher quintiles rely more on capital income than do lower quintiles, the reduction in the relative return to capital exerts a progressive influence. A second contributing factor is the nature of recycling. The additional progressive influence is strongest when recycling is via lump-sum rebates, reflecting the fact that the rebates (of equal value for every household) are larger relative to the household's benchmark expenditure, the lower the quintile (or benchmark expenditure) of the household. Under the broader measure of welfare, the source-side results are progressive under payroll and individual income tax recycling as well.[38] However, recycling via cuts in corporate income taxes exerts a regressive influence, and thus the full source-side impact usually is approximately proportional in this case.

Third, the source-side impacts are considerably larger when the broader measure is employed. Recycling through cuts in the payroll tax or the individual income tax reduces labor taxes and thereby raises the after-tax wage. This not only increases labor income but also raises the value of leisure. The broader measure captures this latter effect by considering the impact on the labor time endowment.

7.2. Overall welfare impacts

Fig. 6 displays the full welfare impact as measured by the equivalent variation (EV). As indicated in Section 2, this is the sum of the use- and source-side impacts when the interaction term is accounted for. As noted, we embed the interaction component in the use-side impact.[39] Fig. 6 displays the overall welfare impacts based on these comprehensive measures. Again, we show the impacts over the time-intervals 2018–2020, 2018–2040, and 2018–infinity. (See Appendix C for results for particular years.)

The figure reveals that the overall impacts are progressive under recycling via lump-sum rebates: the very progressive source-side impacts outweigh the regressive impacts on the use side. The overall impact is most progressive under lump-sum recycling, reflecting the strong progressive source-side impact of this form of recycling. Under corporate income tax recycling, the absolute size of the impacts is smaller than under the other recycling methods, and the results are close to proportional. Recycling via a corporate income tax cut is especially beneficial to higher-income households on the source side, and as a result the source-side effect is only mildly progressive. This accounts for the fact that the overall (source- plus use-side) impact is the least progressive.

We have offered results across households sorted into quintiles by expenditure, which, as mentioned earlier, is often viewed as a rough proxy for lifetime income. An alternative is to rank households by income. Fig. 7 compares the results under the two sorting methods. Changing the ordering of households mainly alters impacts on the source side, especially for the lowest quintile. Ranking by income puts more retirees in the lowest quintile than when households are ranked by expenditure. Retirees tend to have greater wealth than the average individual in quintile 1 under expenditure ordering. As a result, quintile 1 has more wealth under income ordering than under expenditure ordering. Since the welfare effects are expressed as a percentage of wealth,

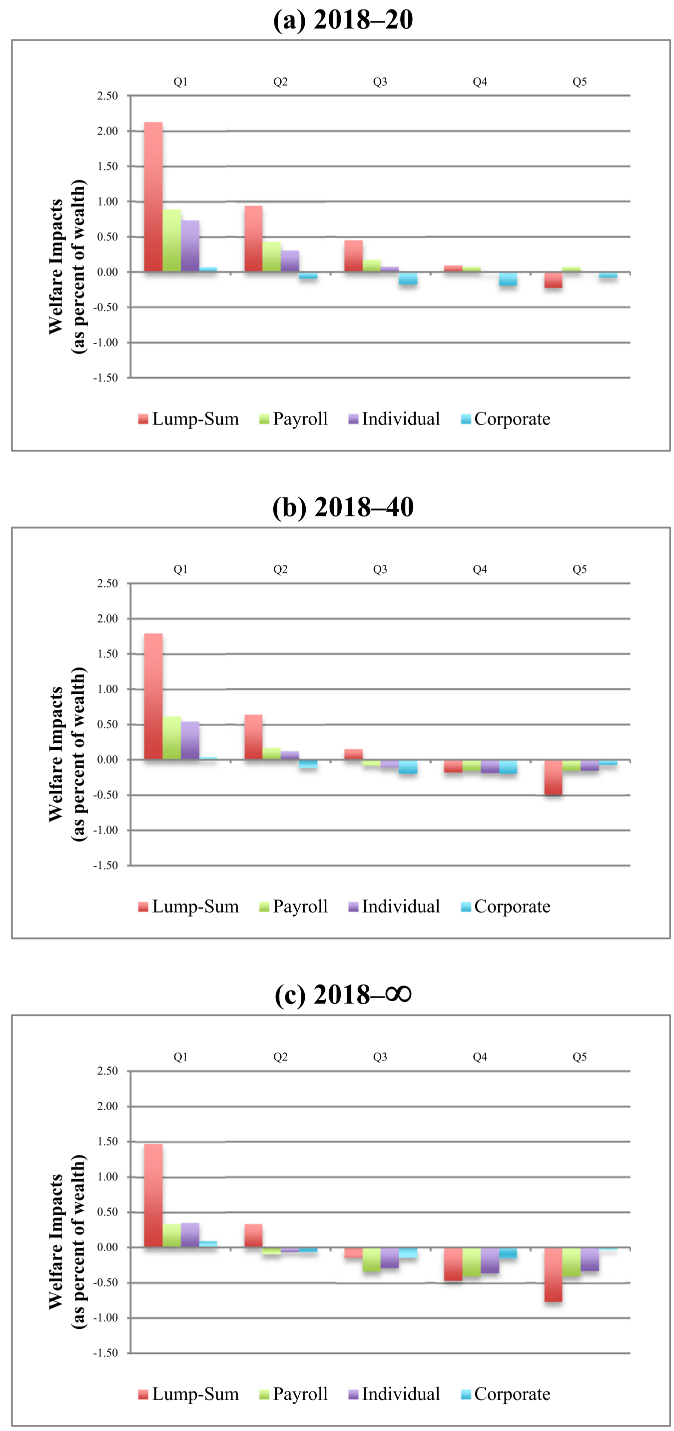


Fig. 6. Overall welfare impacts over time intervals, by quintile.

[38] Under the income-only measure, the results are close to proportional under payroll tax and individual income tax recycling in the nearer term.

[39] Numerically, we find that the interaction term is very small relative to the use-side impact, and that it is very slightly regressive. The interaction term contributes to less than 1.5% of the use-side impact for quintile 1 households, and to less than 1% of the use-side impact for the other quintiles. Thus, including the interaction term increases the measured regressivity of the use-side impact. Given the small size of this term, the impact on the extent of regressivity is very small.

these percentages are often smaller when households are ranked by income. The overall shapes of the impacts are fairly similar.[40]

The general picture emerging from this section is that the source-side impacts tend to be progressive, offsetting the regressivity of the use-side effect. Our results also show that both the scale and the regressivity or progressivity of the overall (use- plus source-side) impacts depend importantly on the method of recycling, which exerts a strong influence on the source side. The extent of progressivity is greatest under lump-sum recycling, although it is significant under payroll tax and individual income tax recycling as well. The overall impact is close to proportional under corporate income tax recycling. The scale of the overall impact is much smaller under corporate income tax recycling than under the other recycling approaches.

Impacts change over time. In the cases involving recycling through cuts in payroll or individual income tax rates, the household groups tend to experience larger welfare losses over time, in keeping with the steady rise in the carbon tax rate. However, in the case of recycling through cuts in the corporate income tax, the scale of the impacts for a given quintile does not change much over time, a reflection of the higher rates of investment and higher incomes associated with the corporate tax cuts. This growing beneficial impact offsets the potentially increasing adverse impact of rising carbon tax rates.

7.3. Impacts in the absence of recycling

It is useful to consider what the impacts would be if, in contrast with the scenarios previously considered, the revenues were not recycled to the private sector. Fig. 8 provides results from simulations involving no recycling: households receive no reductions in tax rates or lump-sum rebates. Results are based on the full (broader) welfare measure. In these simulations, the carbon tax revenue is retained by the government. These results abstract from the distributional impacts of government spending of this revenue.[41] The figure shows results under the same time-intervals considered earlier: 2018–2020, 2018–2040, and 2018–infinity.

The absence of recycling implies that the source-side effect is more negative (or less positive) than in the previously considered cases, since households no longer receive income through lump-sum rebates or enjoy higher after-tax income from tax rate cuts. Under the full welfare measure and over the infinite horizon, in the absence of recycling the source-side impact on the lowest quintile is 0.73% of wealth, as compared with 2.2% under lump-sum recycling. For the highest quintile, the source-side impact is −0.53% of wealth, compared with −0.4% under lump-sum recycling. Each quintile's overall welfare impact is lower when recycling is absent. In this case the variation in distributional outcomes attributable to the different recycling methods no longer applies. Thus, as one might expect, the distribution (as opposed to the magnitudes) of the impacts in the absence of revenue recycling is more uniform than when recycling is present, though the differences are slight.

Fig. 8 shows that over the interval 2018–2040, in the absence of recycling, the carbon tax's welfare impact is equivalent to an increase in wealth of 0.35 for quintile 1. For this quintile, the beneficial source-side impact more than offsets the adverse use-side impact, producing an overall positive impact. In contrast, for the other four quintiles, the adverse use-side impact dominates: the overall welfare impacts for four quintiles 2–5 are −0.15, −0.42, −0.52, and −0.62, respectively, as a percent of wealth.

In the absence of recycling, the total welfare impact across all quintiles (in present discounted value, over the infinite horizon) is $4.7 trillion (in 2013$). This is obtained by adding up the equivalent variations applying to each quintile; it approximates very closely the equivalent variation for the E3 model's single representative household. The total welfare impact is a cost representing 0.77% of reference case aggregate wealth.[42] The revenue yield from the carbon tax over this same horizon is $4.0 trillion (in 2013$).[43] Thus the cost per dollar raised is $1.17. It is important to keep in mind that this cost-per-dollar figure does not account for the benefits from the use of the carbon tax revenue. Nor does it account for the environmental benefits (avoided environmental damages) that result from the carbon tax, benefits that represent the principal rationale for the tax.[44]

Rausch et al. (2011) also assess the distributional impacts in the absence of recycling. They offer an alternative approach to measuring the use- and source-side impacts. Their approach employs two counterfactual simulations. In one, all households are specified as having identical income shares. This simulation focuses on the distributional implications of the use-side impact by indicating what the overall (use- plus source-side) welfare impact would be if the source-side impact were distributionally neutral — that is, if all households experienced the same (average) source-side impact. The authors find that in this case, the overall impact is regressive. We have performed the same use-side-focused simulation with our models and data and obtain similar results.[45]

In their other counterfactual simulation, Rausch et al. (2011) specify all households as having identical expenditure shares. This isolates the distributional implications of the source-side impact by making the use-side impact distributionally neutral. In this case, the authors find a progressive welfare impact. We also obtain a progressive welfare impacts when we implement this approach in our model, but the results from our model and data are more progressive than the results in their paper.[46]

It is worth noting that, in contrast with the main approach used in this paper, the Rausch et al. (2011) approach does not aim to measure the welfare impact attributable to the use-side effect or to the source-side effect. Rather, it focuses on the distributional implications of each effect, and shows what the combined use- and source-side welfare impact would be if one of the two effects, while present, had no distributional impact. Because their approach does aim to measure the separate contributions of the use- and source-side effects to welfare, their method does not depend on the choice of numeraire.

8. Policies with targeted compensation: impacts and trade-offs

Our results suggest that the carbon tax (with recycling) usually is not regressive once one accounts for its impact on the source side. This could suggest that the outcome is acceptable on fairness grounds — that supplementary provisions for compensation are not needed to bring about a desirable outcome. Fairness can also depend on absolute (as opposed to relative) impacts, however. As Fig. 6 indicates, over the longer term, quintiles 2 and 3 experience welfare losses under recycling

[40] Other studies have observed larger differences between the results under expenditure- and income-ranked household groups. For example, Fullerton and Heutel (2010) find that ranking by expenditure implies significantly greater regressivity on the use side. Metcalf et al. (2012) obtain significantly less regressivity in this case.

[41] Our models do not have the detail that would enable us to capture these distributional impacts.

[42] With alternative terminology, we could state that the aggregate willingness to pay, apart from environmental benefits and benefits from recycling, is −0.77% of wealth.

[43] This accounts for the carbon tax's adverse impact on incomes and the associated negative impact on the revenues generated by other taxes.

[44] To get a sense of the value of the climate benefits from the carbon tax, we have applied the model's projected emissions reductions to a central estimate of the "social cost of carbon" (the marginal damage per ton of CO_2 emissions) from the US government's Interagency Working Group (2016, estimate using 3% discount rate). This resulting estimate benefit amounts to 0.61% of total wealth. As discussed in Goulder and Hafstead (2017), the benefits of reduced local air pollution appear to exceed the direct climate benefits from pricing carbon.

[45] For example, the average impact in this scenario in Rausch et al. (2011) ranged from −0.91% of full income for the lowest decile to −0.65% for the highest decile; with our models and data, we obtain results that range from −0.89% of wealth for the lowest quintile and −0.71% for the top quintile.

[46] In Rausch et al. (2011), the average impact in this scenario ranges from −0.36% for the lowest quintile to −0.70% for the highest one. With our data and models, we obtain welfare impacts that range from 0.16% to −0.96% for these quintiles, respectively.

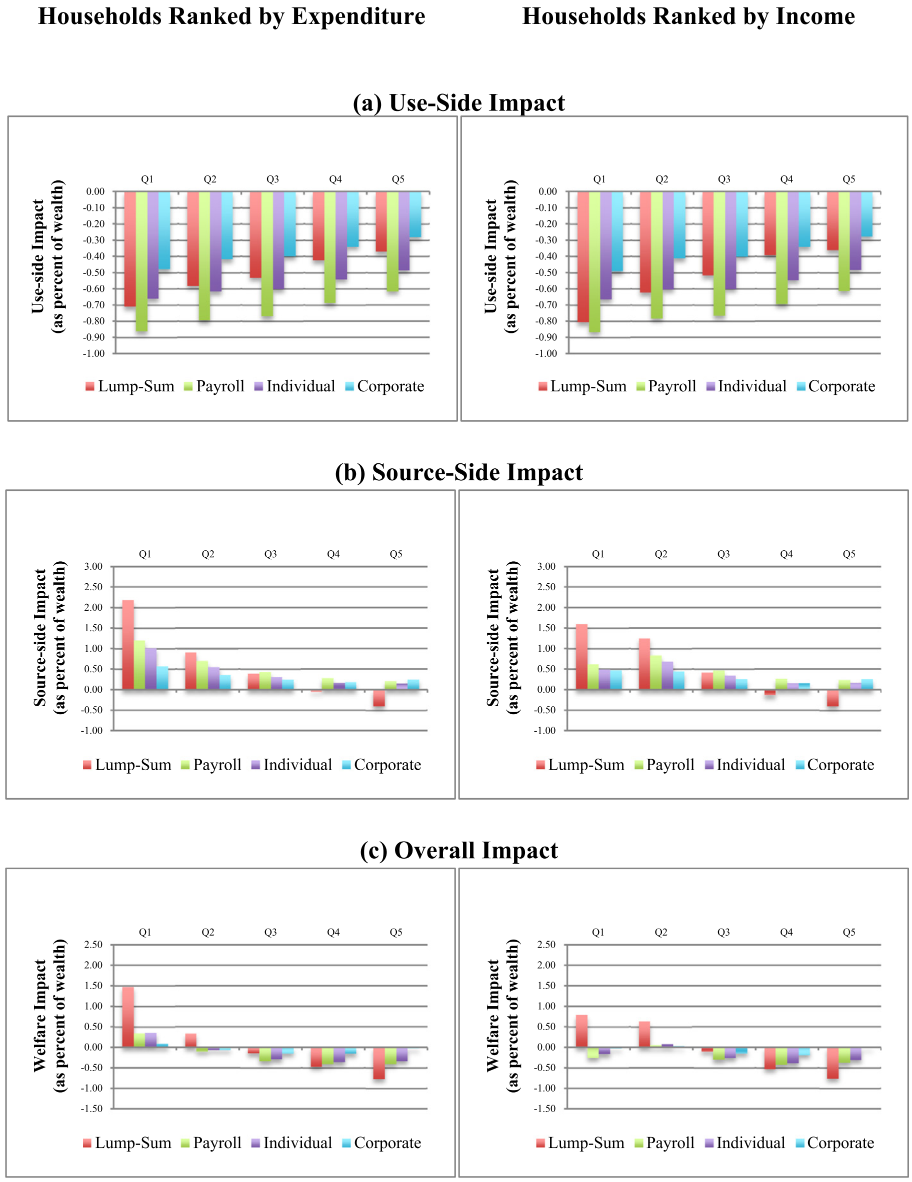


Fig. 7. Distributional impacts over the infinite horizon under alternative orderings of households (using full welfare measure).

involving marginal rate cuts. (The lowest quintile enjoys gains under all forms of recycling.) To the extent that considerations of fairness call for reducing the impacts on these groups of households, it is worth considering the potential trade-off in avoiding adverse impacts.

Here we apply the numerical models to quantify this potential trade-off. We examine the impacts of two sets of “hybrid” policies that involve a combination of recycling through lump-sum rebates and recycling through cuts in payroll, individual, or corporate income tax rates. Some of the net revenue from the carbon tax is devoted to lump-sum rebates, while the rest is devoted to one of the three tax cuts. In the rebate and tax cut combination, the rebates are targeted either (a) to lowest two income quintiles at a level just sufficient to prevent a welfare loss to the second quintile or (b) to the lowest three income quintiles at a level just sufficient to prevent a welfare loss to the third quintile. The total rebate is split evenly across the two (in case a) or three (in case b) quintiles that receive the targeted compensation.

Fig. 9 shows the distribution of welfare impacts from the hybrid policies and the previously discussed “pure” policies involving recycling through lump-sum rebates alone or tax cuts alone under the full infinite-horizon welfare measure. The top and bottom panels display outcomes for the hybrid policies designed to prevent a welfare loss to quintile 2 (upper figure) or quintiles 2 and 3 (lower figure). Under the former hybrid policies, quintiles 1 and 2 are better off relative to the corresponding pure recycling policies, while quintiles 3–5 are slightly worse off. Under the latter hybrid policies, the differences between the hybrid and pure policies are starker, as quintile 3 requires very large rebates as targeted compensation to avoid adverse welfare impacts (and, by design, quintiles 1 and 2 also receive these significant rebates).[47]

Table 9 compares the economy-wide welfare costs in the hybrid cases with those in the pure recycling cases. Targeted compensation raises overall costs by reducing the amount of remaining revenue for financing cuts in distortionary taxes. The table shows that the cost increases are quite sensitive to both the way that remaining revenues are to be recycled and the span of the groups targeted for compensation. Lump-sum compensation has an opportunity cost: it reduces the

[47] More complex policies could involve levels of compensation that were differentiated across the targeted quintiles in such a way as to prevent an increase in welfare to the representative household in any of the targeted quintiles.

amount of revenue available to finance cuts in distortionary taxes.[48] This opportunity cost is highest when compensation takes away revenues that otherwise would have been used to cut corporate income taxes. As mentioned earlier, the corporate tax is the most distortionary among the taxes compared in Table 9; hence the lowered ability to reduce the corporate tax rate is especially costly. For any given recycling method, the cost of compensation is an order of magnitude higher under the more ambitious hybrid policy that prevents a welfare loss to both quintiles 3 and 2, a reflection of the much higher level of lump-sum rebates required under this policy. We leave it to the reader to assess the importance of the distributional objectives served by these policies and decide whether achieving these objectives is worth the sacrifice of efficiency.

9. The role of transfer income

As discussed in Section 7, increases in nominal transfer income are a key factor behind the positive and progressive source-side impacts under most recycling options. Under current US policy, nearly all government transfers are indexed to inflation. Accordingly, in our central analysis, we assume in both the E3 and DH models that the time profile of transfers is maintained in real terms for every representative household. By raising the prices of consumer goods, a carbon tax leads to an increase in the price level, which necessitates an increase in nominal transfers. Higher transfers contribute to a positive source-side impact.

To gauge the contribution of transfer indexing to the overall impact on the source side, we consider a counterfactual case where households in the DH model receive fixed nominal transfers. Fig. 10 offers a comparison of results in the indexed transfers (left side) and fixed nominal transfers (right side) cases. In the figure, the results involve the full source-side measure that includes changes in the value of leisure and changes in savings rates. When transfers are not indexed, the potential beneficial source-side impact from indexing is absent, and the overall source-side impacts are slightly regressive under tax recycling options. Thus the progressive source-side impacts in our main analysis under tax recycling options are strongly driven by policy-induced increases in nominal transfer income.

The left and right columns of Fig. 11 display the overall welfare impacts across households for three time intervals in cases of indexed and fixed (nonindexed) nominal transfers. Over the longer term, the welfare impact is negative for all households under all recycling options when transfers are fixed in nominal terms, except for quintile 1 under recycling via lump-sum rebates. As in the earlier cases involving indexed transfers, the outcome is strongly progressive under lump-sum recycling. But in contrast with the indexed transfers case, the impact under other forms of recycling is regressive, reflecting both the regressive use- and source-side impacts in the absence of transfer income. These results reinforce the arguments in Fullerton et al. (2011) and Cronin et al. (2017) that the indexing of transfers contributes significantly to progressive outcomes. In fact, in the DH model, indexing completely mitigates the adverse impacts of a carbon tax on the average household in the lowest expenditure quintile.

10. Conclusions

We have examined the distribution of the impacts of a carbon tax across US households, considering both source- and use-side impacts under a variety of revenue-recycling scenarios.

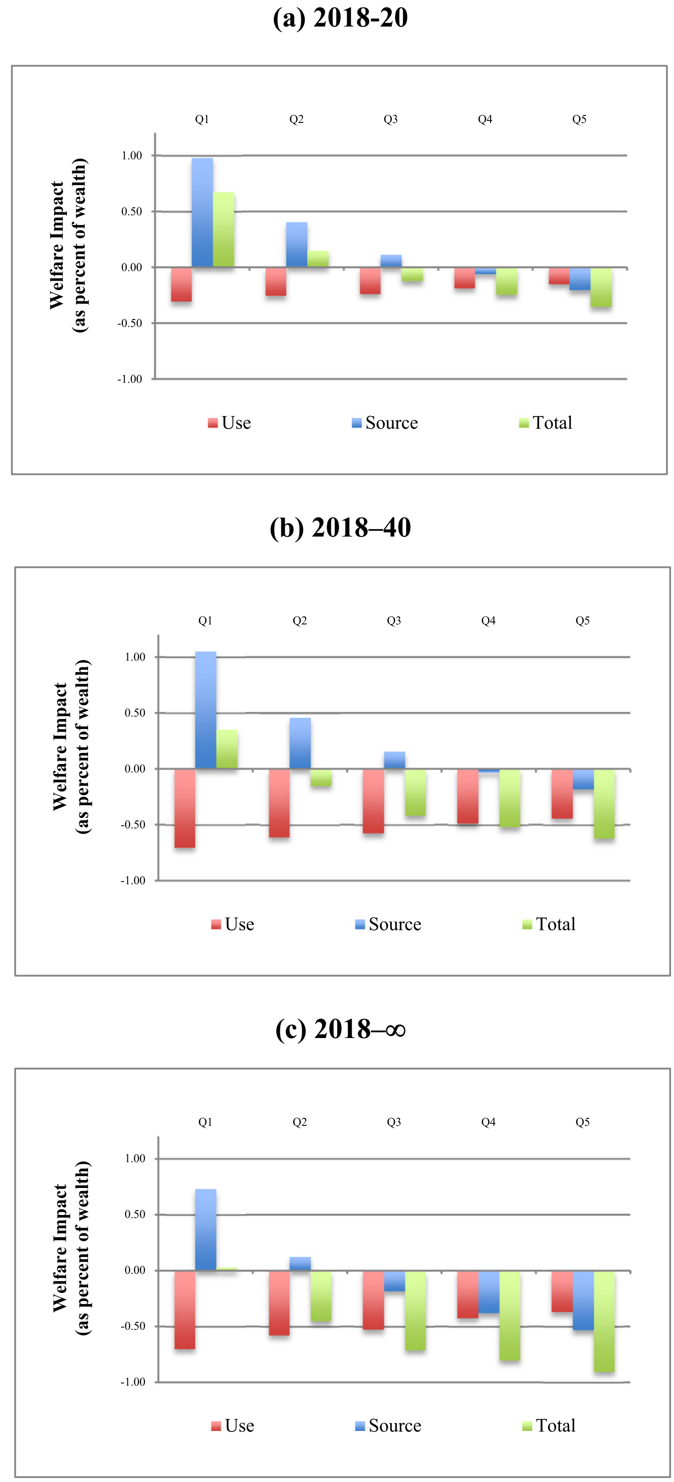


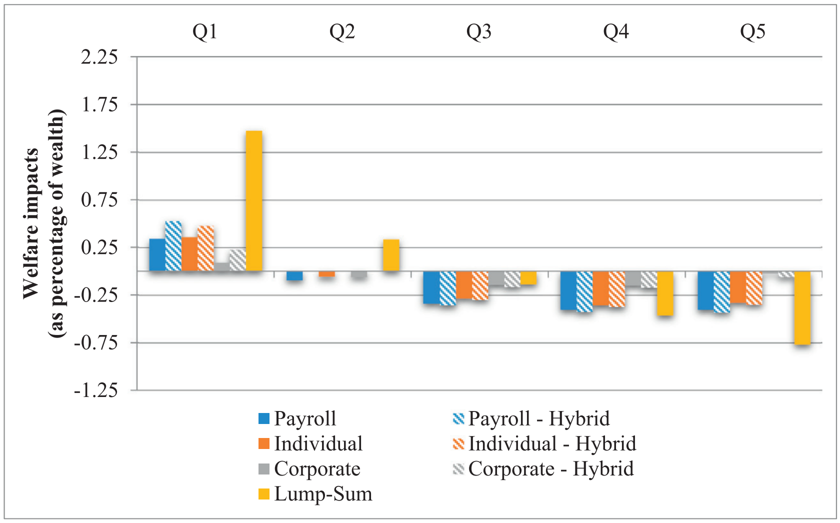
Fig. 8. Use, source, and overall welfare impacts over time intervals, by quintile, in the absence of revenue recycling.

We find that under a range of recycling methods, the use-side impacts are consistently regressive, while the source-side impacts are usually progressive. The source-side impacts tend to more than fully offset the use-side impacts, so the overall impact is either progressive or close to proportional. Our approach reveals that the distributional impacts — particularly on the source side — are sensitive to the nature of recycling.

Our approach differs methodologically from earlier studies in several ways. We offer an analytical approach that employs broader measures of the source- and use-side effects; in contrast with more conventional

[48] Under the hybrid policies that prevent a welfare loss to the representative household in the second quintile, the targeted lump-sum compensation reduces gross revenues available for payroll, individual, and corporate tax cuts by 1.7, 1.1, and 1.1%, respectively. Under the more extensive hybrid policy that prevents a welfare loss to the representative household in both the second and third quintiles, compensation reduces gross revenues for cuts in payroll, individual, and corporate taxes by 16.9, 15.6, and 10.8%, respectively.

(a) Targeted Compensation to Prevent Loss to Quintile 2



(b) Targeted Compensation to Prevent Loss to Quintiles 2 and 3

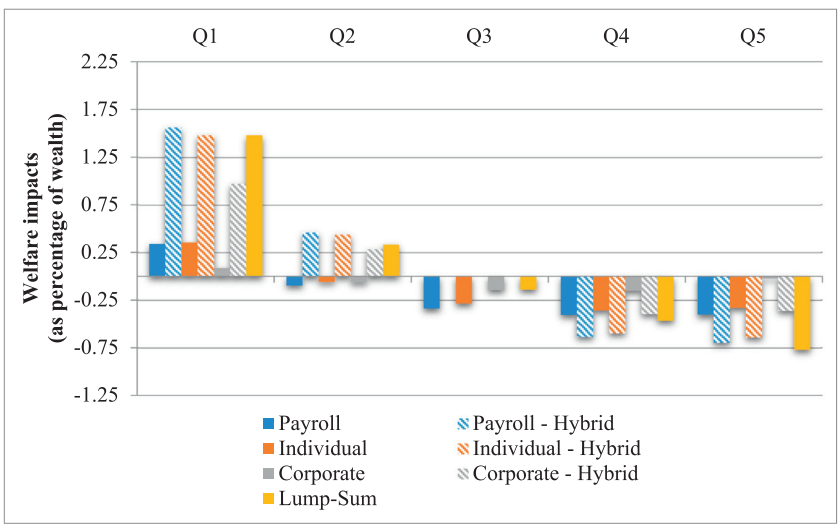


Fig. 9. Results under "pure" and "hybrid" revenue recycling impacts over the infinite horizon, by quintile.

measures, our measures together add up to the full welfare impact. In addition, we consider a range of recycling methods as well as a case where the government does not recycle the revenues. And we assess the relative contribution of source- and use-side impacts to the overall welfare impact on each household group.

Ours is not the first study to find that the overall impact of a carbon tax can be progressive. Some recent studies that consider both the source- and use-side impacts have reached a similar conclusion. However, in contrast with earlier studies, we find that under plausible assumptions, the lowest household income quintile does not suffer an absolute reduction in welfare under the carbon tax.[49] We also find larger source- and use-side impacts than what the narrower welfare measures used in previous studies would predict.

Inflation-indexed government transfers very significantly influence the distributional impacts of climate policy. They avoid what otherwise would be significantly regressive overall impacts providing additional nominal transfers to compensate for higher overall consumer prices from climate change policy. Since transfers represent an especially large share of income for low-income households, the increase in nominal transfers exerts a significant progressive impact.

We apply our general equilibrium model to assess the costs of including targeted compensation as part of a carbon tax policy. The costs of avoiding adverse impacts depend critically on the method of recycling and the particular target involved. The costs of compensation are about an order of magnitude higher when remaining revenues are to be used for corporate income tax cuts than when the remaining revenues are used in other ways. These efficiency costs also are an order of magnitude higher under the more ambitious hybrid policy of avoiding

[49] In contrast, Goulder and Hafstead (2017) show that in the absence of compensation, firms in some industries would suffer significant profit losses, with significant impacts on the wealth of owners of these firms. This suggests that providing compensation to certain industries might be critical to the political feasibility of a carbon tax.

Table 9
Aggregate welfare costs of a carbon tax with and without targeted compensation.

	Tax rate recycling method		
	Payroll tax cuts	Individual income tax cuts	Corporate tax cuts
No targeted compensation			
Welfare costs[a]	\$2046.83	\$1684.82	\$380.99
- per ton of CO_2 reduced	\$37.63	\$31.08	\$7.25
Targeted compensation to prevent adverse impact on quintile 2[b]			
Welfare costs[a]	\$2075.97	\$1716.51	\$468.40
	(1.4%)	(1.9%)	(22.9%)
- per ton of CO_2 reduced	\$38.16	\$31.66	\$8.90
	(1.4%)	(1.9%)	(22.7%)
Targeted compensation to prevent adverse impact on quintiles 2 and 3[b]			
Welfare costs[a]	\$2345.02	\$2155.90	\$1222.72
	(14.6%)	(28.0%)	(220.9%)
- per ton of CO_2 reduced	\$43.03	\$39.63	\$22.93
	(14.3%)	(27.5%)	(216.2%)

[a] Welfare costs are the negative of the equivalent variation, expressed in billion 2013\$.
[b] Numbers in parentheses express percentage changes in welfare costs relative to the "no targeted compensation" case.

Fig. 10. Source-side impacts over time intervals, full measure, by quintile.

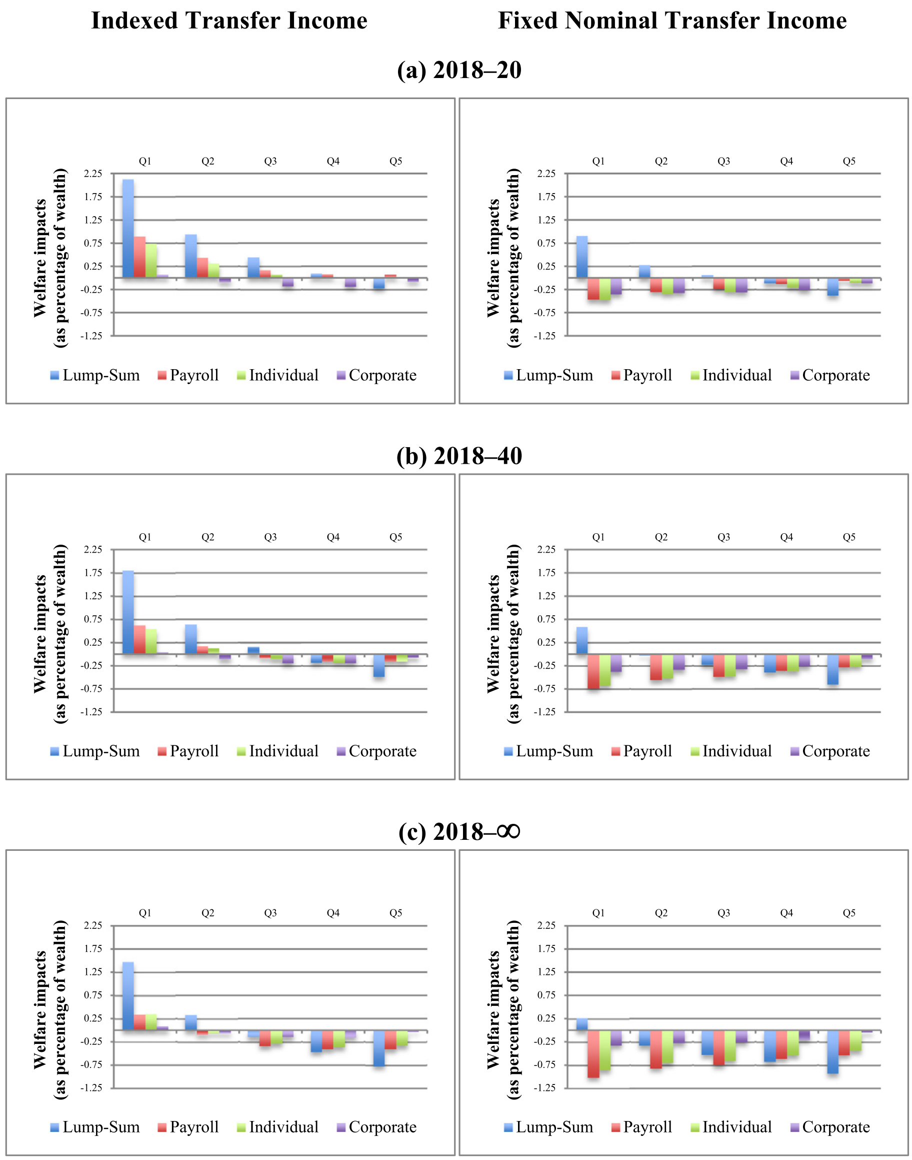


Fig. 11. Overall welfare impacts over time intervals, by quintile.

an adverse impact on the middle quintile, a reflection of the much higher level of rebates required under this policy.

Two caveats are in order. First, our analysis has not considered the extent of heterogeneity of impacts within quintiles.[50] Second, we have considered the distributional impacts across only one household dimension — income. Fairness (and political feasibility) of climate policy can depend on the distribution along other demographic dimensions.

These results underscore the importance of an integrated approach to distributional analysis, one that considers closely the use of policy-generated revenues and the nature of existing government transfer programs. In addition, they reveal that one's conclusions as to the distributional consequences of policies depend on the welfare measure employed. We find that the results under the more comprehensive measures we have introduced differ significantly from those under the narrower, more conventional measures.

[50] Cronin et al. (2017) analyze policies involving redistribution of carbon tax revenues, accounting for heterogeneity within income groups. Fischer and Pizer (2017) examine how to account for household heterogeneity in the evaluation of carbon taxes and tradable performance standards. One dimension along which households differ is saving behavior. Because of differences in savings rates, some households might move from one quintile to another over the life cycle, while others might not. The relative endowments of labor and capital of households initially in the same quintile can diverge as well. An effective treatment of these issues would require an overlapping generations model.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jpubeco.2019.04.002.

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