The Distributional Effects of a Carbon Tax on Current and Future Generations

Stephie Fried*, Kevin Novan†, William B. Peterman‡

February 1, 2018

Abstract

This paper uses a life cycle model to compare how different approaches for recycling carbon tax revenue affect the welfare of agents born in the future steady state versus agents alive when the policy is adopted. Our results demonstrate that the welfare consequences of a given policy vary substantially across these two groups. For agents born into the future steady state, the expected non-environmental welfare costs are minimized when carbon tax revenue is used to reduce an existing distortionary tax. In contrast, among the agents alive when the policy is adopted, recycling revenue through uniform, lump-sum rebates results in the largest welfare increase across the policies we examine. Moreover, we find that the regressivity or progressivity of a policy also differs within the living population versus the future steady state population. Overall, our results illustrate that estimates of the non-environmental welfare costs of carbon tax policies that are based on the long-run outcomes miss-represent the near-term consequences. Given the potential importance of these near-term effects on the political feasibility of a policy, our findings indicate that, when designing a carbon tax, policy makers must pay careful attention to not only the long-run outcomes, but also to the transitional welfare effects of the policy.

Keywords: Carbon taxation; overlapping generations
JEL codes: E62; H21; H23

*Arizona State University, W.P. Carey School of Business. Email: sdfried@asu.edu

†University of California, Davis, Department of Agricultural and Resource Economics. Email: knovan@ucdavis.edu

‡Federal Reserve Board of Governors. Email: william.b.peterman@frb.gov. Views expressed in this paper are those of the authors' and do not reflect the views of the Federal Reserve System or its staff.

For helpful feedback and suggestions, we thank seminar participants at the Econometric Society North American Summer meetings (2016), AERE Summer Conference (2016), QSPS (2016), the University of Connecticut, the Federal Reserve Board of Governors, and the University of California San Diego. Additionally, we thank four anonymous referees for their many suggestions.

1 Introduction

Establishing a price on carbon, using either a carbon tax or a cap-and-trade program, is well understood to be the most efficient approach for reducing greenhouse gas emissions (Pigou (1920), Dales (1968), Montgomery (1972), Baumol and Oates (1988)). Importantly, establishing a carbon price could also generate a substantial stream of government revenue.[1] This raises an obvious question – how should this revenue be used?

Often, policymakers propose recycling carbon tax revenue in a way that differs from the approach advocated by the economic literature. For example, one prominent proposal for a carbon tax was put forth by the Climate Leadership Council (CLC).[2] The proposal calls for the U.S. federal government to impose a carbon tax with all revenue returned to individuals through uniform, lump-sum payments. In contrast, the economic literature suggests that it would be far more efficient to use the revenue to reduce pre-existing distortionary taxes (e.g., taxes on labor or capital income) – a result referred to as the 'weak double-dividend hypothesis' (Goulder (1995), de Mooij and Bovenberg (1998), Bovenberg (1999)).[3] It is important to note, however, that the double-dividend studies largely focus on the long-run welfare consequences of revenue-neutral carbon tax policies. In this paper, we examine how different approaches for recycling carbon tax revenues affect the welfare not only of agents born into the future steady state, but also agents alive at the time the policy is adopted. Our results reveal that a given policy can have dramatically different impacts on the current living population compared to agents born in the future steady state.

To examine the welfare impacts of revenue-neutral carbon tax policies, we follow the macro public finance literature (e.g., Castaneda et al. (2003), Conesa and Krueger (2006),

[1] A report from the U.S. Department of the Treasury (Horowitz et al. (2017)) estimates that a carbon tax starting at \$49 per ton of CO_2 in 2019, and rising to \$70 by 2028, would generate \$2.2 trillion over ten years. Similarly, estimates from the U.S. Congressional Budget Office suggest that setting a modest CO_2 price of \$20/ton would raise \$1.2 trillion in revenue during the first decade the policy is in place (CBO (2011)).

[2] The CLC was initially started by a group including former secretaries of state, James A. Baker III and George P. Shultz; former chairmen of the Council of Economic Advisors, Martin Feldstein and Gregory Mankiw, and former treasury secretary Henry Paulson Jr.

[3] Previous studies also highlight that the revenue recycling method can substantially alter the distribution of the welfare changes across income groups (Fullerton and Heutal (2007), Dinan and Rogers (2002), Metcalf (2007), Parry (2004), Parry and Williams (2010)).

Conesa et al. (2009), Peterman (2013)) and construct a quantitative, overlapping generations model (OLG) which incorporates idiosyncratic productivity shocks, mortality risk, retirement, and Social Security. Using the model, we explore the welfare consequences of imposing a $35 per ton tax on CO_2. This value is in line with the central estimate of the social cost of carbon previously used in cost-benefit analyses performed by the U.S. Government.[4] The revenue from this tax is used to either (1) offset revenue generated by a tax on labor income, (2) offset revenue from a tax on capital income, or (3) is returned in the form of uniform, lump-sum payments. Consistent with the previous work in the double-dividend literature, we abstract from the welfare consequences of improvements in environmental quality and instead focus on the welfare effects stemming from non-environmental channels.[5]

Focusing first on the steady state outcomes, our results echo the findings from the existing literature. Among agents born into the future steady state, the expected non-environmental welfare costs of a carbon tax policy are lower when the carbon tax revenue is used to reduce either existing distortionary tax. In fact, we find that using the carbon tax revenue to offset revenue generated by the capital tax leads to an increase in the expected non-environmental welfare, suggesting that the policy actually reduces the distortions caused by the tax system. In contrast, recycling the revenue in the form of uniform, lump-sum payments – consistent with the recent CLC proposal – results in a decrease in the expected non-environmental welfare of agents born into the future steady steady.

However, our results reveal that revenue-neutral carbon tax policies affect the welfare of the current living agents very differently than the welfare of agents born into the future steady state. In particular, we find that using carbon tax revenue to reduce the labor or capital tax will be far more costly among the living population as opposed to the future steady state cohorts. In contrast, the lump-sum rebate policy is far less costly for the living population, actually leading to an increase in average welfare. Interestingly, among the three policies we consider, the uniform lump-sum rebate results in the largest reduction in

[4]For example, the IAWG (2013) reports a central carbon cost estimate of $38/ton of CO_2 in 2015 dollars.

[5]However, across each of the policy options we simulate, the reduction in energy consumption is very stable. As a result, the welfare changes driven by environmental quality improvements would likely similar across the policies we consider.

expected steady state welfare but also the largest increase in average welfare among the living population. Moreover, our results highlight that, not only do the average welfare impacts vary depending on how the carbon tax revenue is recycled, the regressivity or progressivity of a given policy also varies with whether we focus on the living population or the future steady state population.

Throughout our analysis, we highlight two factors that cause the welfare impacts to differ among the current living agents versus those born into the future steady state. First, following the adoption of a carbon tax policy, the factor prices do not immediately adjust to their new, long-run equilibrium levels. Second, unlike agents born into the steady state, agents alive when the carbon tax is adopted only experience the policy for a portion of their lifetime. This proves to be important because the impact a carbon tax policy has on an agent's remaining lifetime welfare varies substantially with the agent's age.

The present paper builds on several studies examining the transitional welfare impacts of carbon tax policies. Leach (2009) combines an OLG model with a climate model to explore how the environmental and non-environmental welfare impacts of a carbon tax policy differ across generations. Similarly, Rausch (2013) and Carbone et al. (2013) examine the non-environmental welfare impacts of alternative revenue-neutral carbon tax policies using life cycle models.[6] All three of these previous studies examine models with a single representative agent for each age cohort. In contrast, our life cycle model incorporates within age cohort income heterogeneity through individual-specific productivity fixed effects as well as through idiosyncratic productivity shocks.[7] The inclusion of within cohort heterogeneity enables us to directly examine the general equilibrium welfare impacts across both age and income groups.[8] Thus, our welfare measure incorporates the policy's impacts not only on efficiency, but also on equity. In addition, by modeling households' utility using a non-homothetic

[6]Rausch (2013) also consider the impacts of using carbon revenues to reduce the size of the federal debt.

[7]Chiroleu-Assouline and Fodha (2014) also include within-cohort heterogeneity in a life cycle model through the use of ability fixed effects. However, the authors focus solely on the welfare effects of recycling the revenues from a carbon tax through a labor tax rebate in the long run steady state.

[8]In a related analysis, Williams et al. (2015) predict distributional impacts using the estimates from Carbone et al. as inputs in a partial equilibrium, microsimulation model. The model translates the predicted income changes into estimates of the welfare impacts across income groups during the initial year the policy is in place – not over the agents' lifetimes.

utility function, we are able to incorporate the fact that low income households use a higher share of their expenditures on energy, making the carbon tax by itself regressive.

To be clear, the objective of our analysis is not to exhaustively evaluate the full range of revenue-neutral carbon tax policy options available to policymakers. Instead, our goal is to illustrate an important point. Specifically, the welfare and distributional impacts of revenue-neutral carbon tax policies can differ dramatically across agents living during the transition and those born into the future, long-run steady state.[9] Given that the current living agents – not agents born into a future steady state – are ultimately responsible for implementing a carbon tax, it is particularly important to understand the near-term welfare impacts of alternative policies in order to design a politically feasible option. Our findings suggest that it is more beneficial to the living population to return carbon tax revenue through uniform, lump-sum rebates instead of through reductions in distortionary taxes, and thus, the lump-sum rebate approach may in fact be the easier policy to implement.

The remainder of the paper proceeds as follows. Section 2 introduces the OLG model. Section 3 discusses the functional forms in the model and the calibration of the key parameters. Section 4 compares the aggregate welfare and distributional impacts under the alternative carbon tax policies in the long-run steady state and within the current living population. Section 5 concludes.

2 Model

2.1 Demographics

Agents enter the model when they start working, which we approximate with a real world age of 20, and can live to a maximum age of J. Thus, there are $J - 19$ overlapping generations. A continuum of new agents is born each period and the relative size of the newborn cohort grows at a constant rate, n. Lifetime length is uncertain and mortality risk varies over the

[9]Previous studies in the macroeconomic and public finance literatures highlight that, across a variety of settings, the steady state and transition welfare effects of tax policies can differ substantially (e.g., see Domeij and Heathcote (2004), Fehr and Kindermann (2015), Dyrda et al. (2015)).

lifetime. Parameter Ψ_j denotes the probability an agent lives to age $j+1$ conditional on being alive at age j. All agents who live to age J die with probability one the following period, i.e. $\Psi_J = 0$. Since agents are not certain how long they will live, they may die with positive asset holdings. In this case, we treat the assets as accidental bequests and redistribute them lump-sum across all living individuals during period t in the form of transfers T_t^a. All agents are forced to retire at the exogenously determined age j^r.

2.2 Households

An individual is endowed with one unit of productive time per period that can be divided between labor and leisure. In period t, at age j, agent i earns labor income $y^h_{i,j,t} \equiv w_t \cdot \mu_{i,j,t} \cdot h_{i,j,t}$, where w_t is the market wage-rate during period t, $h_{i,j,t}$ denotes hours worked, and $\mu_{i,j,t}$ is the agent's idiosyncratic productivity. Following Kaplan (2012), the log of an agent's idiosyncratic productivity consists of four additively separable components,

$$\log \mu_{i,j,t} = \epsilon_j + \xi_i + \nu_{i,j,t} + \theta_{i,j,t}. \tag{1}$$

Component ϵ_j governs age-specific human capital and evolves over the life cycle in a predetermined manner. Component $\xi_i \sim NID(0, \sigma_\xi^2)$ is an individual-specific fixed effect (i.e. ability) that is observed when an agent enters the model and is constant for an agent over the life cycle. Component $\theta_{i,j,t} \sim NID(0, \sigma_\theta^2)$ is an idiosyncratic transitory shock to productivity received every period, and $\nu_{i,j,t}$ is an idiosyncratic persistent shock to productivity, which follows a first-order autoregressive process:

$$\nu_{i,j,t} = \rho \nu_{i,j-1,t-1} + \psi_{i,j,t} \text{ with } \psi_{i,j,t} \sim NID(0, \sigma_\nu^2) \text{ and } \nu_{i,20,t} = 0. \tag{2}$$

Thus, the average labor productivity of agents differs across cohorts along one dimension, their age-specific human capital, ϵ_j. Agents within an age cohort are differentiated along three dimensions that affect their labor productivity: their ability, ξ_i, their current transitory shock, $\theta_{i,j,t}$, and their current persistent shock, $\nu_{i,j,t}$. Different ability types, and the initial realization of the i.i.d. shock, $\theta_{i,j,t}$, generate an initial productivity distribution within the cohort of 20 year old entrants to the model. Different realizations of the persistent shock $\nu_{i,j,t}$ over the lifetime cause the within cohort variation to grow with age.

We assume that agents cannot insure against idiosyncratic productivity shocks by trading explicit insurance contracts. Moreover, we assume that there are no annuity markets to insure against mortality risk. However, agents are able to partially self insure against labor-income risk by purchasing risk-free assets, $a_{i,j,t}$, that have a pre-tax rate of return, r_t.

Agents split their income between investing in the risk-free asset and consumption. When considering how a carbon tax would affect individuals' consumption, it is important to note that carbon emitting energy sources are not only used in the production of final consumer goods, but carbon-based energy sources are also consumed directly by individuals as a final good (e.g., electricity, gasoline, heating oil, etc.). Therefore, in our model, agents can consume a generic consumption good, $c_{i,j,t}$, as well as a carbon emitting energy good, $e^c_{i,j,t}$.

As previous studies highlight (Metcalf (2007), Hassett et al. (2009)), the direct impact of a carbon tax – prior to any revenue recycling – is likely to be regressive. This is due to the fact that lower income households devote a larger share of their budgets to energy. To ensure that our model captures this negative relationship between income and energy consumption shares, we assume that all agents must consume a minimum amount of energy, $\bar{e}$, and that agents derive no utility from the energy consumed up to this subsistence level.[10]

In each period, an agent chooses labor, savings, generic consumption, and energy consumption, subject to their budget constraint, in order to maximize their expected stream of future discounted lifetime utility given by

$$u(c_{i,j,t}, e^c_{i,j,t} - \bar{e}, h_{i,j,t}) + \mathbb{E}\left\{\sum_{k=j+1}^{J} \beta^{k-j} \prod_{q=j}^{k-1} (\Psi_q) u(c_{i,k,t+k-j}, e^c_{i,k,t+k-j} - \bar{e}, h_{i,k,t+k-j})\right\}. \quad (3)$$

We take the expectation in equation (3) with respect to the stochastic processes governing the

[10] Pizer and Sexton (2017) highlight that variation in energy expenditure shares can also arise within income groups (e.g., $\bar{e}$ could vary across urban and rural locations). We abstract from this variation, effectively assuming that spatial heterogeneity in $\bar{e}$ is uncorrelated with idiosyncratic productivity shocks.

idiosyncratic productivity shocks. Agents discount future utility by β, the discount factor. In addition, they incorporate mortality risk by discounting the next period's utility by Ψ_j. An agent's utility increases with consumption of either energy or the generic consumption good and decreases with more hours worked.

2.3 Production

Perfectly competitive firms produce a generic final good, Y_t, from capital, K_t, aggregate labor (measured in efficiency units), N_t, and carbon-emitting energy, E_t^p, according to the production function, $Y_t = f(K_t, N_t, E_t^p)$. The final good is the numeraire and can be used for, consumption, investment, and to purchase energy at exogenous price p^e.

This model of production with an exogenous energy price is consistent with the assumption that the country behaves as a small open economy with respect to energy. The country imports energy at price p^e in exchange for the final good with zero trade balance in every period. This of course assumes that the energy price would not respond to changes in demand caused by the climate policy. In practice, this is likely to be a minor simplification. In our carbon tax simulations, U.S. energy consumption falls approximately fifteen percent, which would represent a very small (2.4 percent) change in global energy demand, suggesting that the resulting general equilibrium effects of unilateral U.S. climate policy on global energy prices are also likely to be small.[11]

To provide insight into how a decrease in energy prices – which is driven by the adoption of a domestic carbon tax – could affect our results, we also analyze a two-sector model in which all energy is produced domestically from capital and labor and the final good is produced from capital, labor, and domestic energy, as in Barrage (2016). While assuming that energy prices are constant will certainly understate the response of energy prices to a carbon tax, assuming all energy is produced in a domestic energy sector will certainly

[11] In 2012, U.S. carbon-energy use accounted for approximately 16 percent of global carbon-energy use. We calculate the U.S. fraction of carbon-energy from the ratio of U.S. carbon emissions to global carbon emissions. We use emissions data as opposed to data on energy production and/or consumption because the emissions data capture all U.S. carbon-related activities. Data on carbon emissions are from the EIA international energy statistics: http://www.eia.gov/.

overstate the endogenous response of the energy price to a carbon tax policy. Therefore, our main model (i.e. assuming a constant world energy price) and our robustness check effectively bound the potential responses of energy prices to a domestic carbon tax policy. We find that while there are small quantitative differences, the results do not change qualitatively with the assumption of a constant versus variable energy price.

2.4 Government Policy

The government performs three activities: (1) it consumes resources in an unproductive sector, G, (2) it runs a pay-as-you-go Social Security system, and (3) it taxes capital income, labor income, and energy (i.e. a carbon tax) to finance G. The government pays Social Security benefits, S_t, to all agents that are retired. Each agent receives a constant payment each period, which is independent of the specific agent's lifetime earnings. The government finances the Social Security system with a flat tax on labor income, τ_t^s. Half of the payroll taxes are withheld from labor income by the employer and the other half are paid directly by the employee. The payroll tax rate is set such that the Social Security system has a balanced budget in every period.

The government taxes each agent's capital income, $y_{i,j,t}^k$, according to a constant marginal tax rate, τ^k. An agent's capital income is the return on her assets plus the return on any assets she receives as accidental bequests, $y_{i,j,t}^k \equiv r_t(a_{i,j,t} + T_t^a)$. The government taxes labor income according to a progressive tax schedule, $T^h(\tilde{y}_{i,j,t}^h)$, where $\tilde{y}_{i,j,t}^h$ denotes the agent's taxable labor income. A working agent's taxable labor income is her labor income, $y_{i,j,t}^h$, net of her employer's contribution to Social Security which is not taxable under U.S. tax law. Thus, $\tilde{y}_{i,j,t}^h \equiv y_{i,j,t}^h(1 - \tau_t^s/2)$, where $(\tau_t^s/2)y_{i,j,t}^h$ is the employer's Social Security contribution. Consistent with U.S. tax law, for agents whose annual income exceeds a given threshold, the government also taxes a portion of their Social Security benefits at the labor income tax rate. The taxes paid on an agent's Social Security benefits are defined by $T^s(S_t, y_{i,j,t}^k)$.

Finally, the government can tax carbon energy at a constant rate. This tax not only raises government revenue, but it can also reduce the use of carbon based energy. The carbon tax,

τ^c, is designed to place a price on the externality, carbon. Thus, the government applies the tax per unit of energy consumed, raising the price of energy from p^e to $p^e + \tau^c$.[12] In one of the tax policies, the government rebates this carbon-tax revenue through uniform lump-sum transfers to the households, T^c_t.

2.5 Definition of a Stationary Competitive Equilibrium

In this section, we define a stationary competitive equilibrium. In the long-run steady state, the factor prices, tax parameters, and aggregate macroeconomic variables will be constant. The individual state variables, x, are asset holdings, a, idiosyncratic labor productivity, μ, and age j. In addition, we signify an agent's chosen level of capital savings in the subsequent period as a'. We suppress the i, j, and t subscripts throughout the stationary equilibrium definition. The summations are taken over the distribution of agents over the state space, x.

Given Social Security benefits, S, government expenditures, G, demographic parameters, $\{n, \Psi_j\}$, a sequence of age-specific human capital, $\{\epsilon_j\}_{j=20}^{j^r-1}$, a labor-tax function, $T^h : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, a capital-tax rate, τ^k, a carbon-tax rate, τ^c, transfers from the climate policy, T^c, an energy price, p^e, a utility function $U : \mathbb{R}_+ \times \mathbb{R}_+ \times \mathbb{R}_+ \rightarrow \mathbb{R}_+$, factor prices, $\{w, r, p^e\}$, and capital depreciation rate δ, a stationary competitive equilibrium consists of agents' decisions rules, $\{c, h, e^c, a'\}$, firms' production plans, $\{E^p, K, N\}$, transfers from accidental bequests T^a, a social security tax rate, τ^s, and the distribution of individuals, $\Phi(x)$, such that the following holds:

1. Given prices, policies, transfers, benefits, and ν that follows equation (2) the agent maximizes equation (3) subject to:

$$\begin{aligned} c + (p^e + \tau^c)e^c + a' = \\ \mu h w(1-\tau^s) + (1 + r(1-\tau^k))(a + T^a) - T^h\big(\mu h w(1 - .5\tau^s)\big) + T^c \text{ for } j < j^r \end{aligned} \tag{4}$$

[12] Given that fossil fuel combustion accounts for over 80 percent of GHG emissions, a carbon tax behaves much like a tax on energy. This of course abstracts from substitution between fossil fuel energy sources with varying carbon intensities that could occur with a carbon tax.

$$c+(p^e+\tau^c)e^c+a' = S - T^s(S,y^k) + (1+r(1-\tau^k))(a+T^a) + T^c \text{ for } j \geq j^r$$

$$c \geq 0,\ e^c \geq 0,\ 0 \leq h \leq 1,\ a \geq 0,\ a_{20} = 0$$

2. Firms' demands for K, N, and E^p satisfy:

$$r = \frac{\partial f(K,N,E^p)}{\partial K} - \delta \tag{5}$$

$$w = \frac{\partial f(K,N,E^p)}{\partial N} \tag{6}$$

$$p^e + \tau^c = \frac{\partial f(K,N,E^p)}{\partial E^p} \tag{7}$$

3. The Social Security tax satisfies:

$$\tau^s = \frac{S\sum_{j\geq j^r}\Phi(x)}{wN} \tag{8}$$

4. Transfers from accidental bequests satisfy:

$$T^a = \sum (1-\Psi)a'\Phi(x) \tag{9}$$

5. The government budget balances:

$$G = \sum \left[\tau^k r(a+T^a) + T^h\big(\mu h w(1-.5\tau^s)\big) + T^s(S,y^k) + \tau^c e^c\right]\Phi(x) + \tau^c E^p - T^c \tag{10}$$

6. Markets clear:

$$K = \sum a\Phi(x), \quad N = \sum \mu h\Phi(x) \tag{11}$$

$$\sum (c + p^e e^c + a')\Phi(x) + G + p^e E^p = Y + (1-\delta)K \tag{12}$$

7. The distribution of $\Phi(x)$ is stationary. That is, the law of motion for the distribution of individuals over the state space satisfies $\Phi(x) = Q_\Phi \Phi(x)$ where Q_Φ is the one-period recursive operator on the distribution.

3 Calibration and Functional Forms

We calibrate the model in two steps. In the first step, we choose parameter values for which there are direct estimates in the data. In the second step, we calibrate the remaining parameters so that certain targets in the model match the values observed in the U.S. economy. Table 1 reports the parameter values.

3.1 Demographics

Agents enter the model at age 20 and are exogenously forced to retire at age $j^r = 66$. If an individual survives until 100, she dies the next period. We choose the conditional survival probabilities based on the estimates in Bell and Miller (2002). We adjust the size of each cohort's share of the population to be consistent with a population growth rate of 1.1 percent.

3.2 Idiosyncratic and Age-Specific Productivity

We calibrate the labor productivity shocks based on the estimates from Appendix E of Kaplan (2012). These parameters governing the permanent, persistent, and transitory idiosyncratic shocks to individuals' productivity are set such that the shocks are distributed

Table 1: Calibration Parameters (Baseline)

Parameter	Value	Target
Demographics		
Retire Age: j^r	66	By Assumption
Max Age: J	100	By Assumption
Surv. Prob: Ψ_j	Bell and Miller (2002)	Data
Pop. Growth: n	1.1%	Data
Firm Parameters		
Capital Share: ζ	0.36	Data
Substitution Elasticity: ϕ	0.5	Van der Werf (2008)
Depreciation: δ	0.083	$\frac{I}{Y} = 25.5\%$
Productivity: A	1	Normalization
Energy price: p^e	0.0025	$\frac{p^e E^p}{Y} = 0.05$
Productivity Parameters		
Persistence Shock: σ_ν^2	0.017	Kaplan (2012)
Persistence: ρ	0.958	Kaplan (2012)
Permanent Shock: σ_ξ^2	0.065	Kaplan (2012)
Transitory Shock: σ_θ^2	0.081	Kaplan (2012)
Preference Parameters		
Conditional Discount: β	0.998	$\frac{K}{Y} = 2.7$
Risk Aversion: θ_1	2	Conesa et al. (2009)
Frisch Elasticity: θ_2	0.5	Kaplan (2012)
Disutility of Labor: χ	55.3	Avg. $h_{i,j} = 0.333$
Subsistence Energy: $\bar{e}$	5.6	$\Delta\Omega = -12.8$
Consumption Energy Share: $1 - \gamma$	0.069	Avg. $\Omega = 10.2\%$
Government Parameters		
Labor Tax Function: Υ_0	0.258	Gouveia and Strauss (1994)
Labor Tax Function: Υ_1	0.768	Gouveia and Strauss (1994)
Labor Tax Function: Υ_2	1.74	Clears market
Capital Tax Rate: τ^k	0.36	Trabandt and Uhlig (2011)
Government Spending: G	0.12	$\frac{G}{Y} = 0.155$

log normally with a mean of one. In particular, the shock parameters are set at $\rho = 0.958$, $\sigma_\xi^2 = 0.065$, $\sigma_\nu^2 = 0.017$ and $\sigma_\theta^2 = 0.081$. To solve the model, we discretize the shocks using two states to represent the transitory and permanent shocks and five states for the persistent shock.[13] We set $\{\epsilon_j\}_{j=20}^{j^r-1}$ to match the average hourly earnings estimated in Kaplan (2012).

3.3 Preferences

Agents have time-separable preferences over a consumption-energy composite, $\tilde{c}_{i,j,t}$, and hours, $h_{i,j,t}$. The utility function is given by

$$U(\tilde{c}_{i,j,t}, h_{i,j,t}) = \frac{\tilde{c}_{i,j,t}^{1-\theta_1}}{1-\theta_1} - \chi \frac{h_{i,j,t}^{1+\frac{1}{\theta_2}}}{1+\frac{1}{\theta_2}} \tag{13}$$

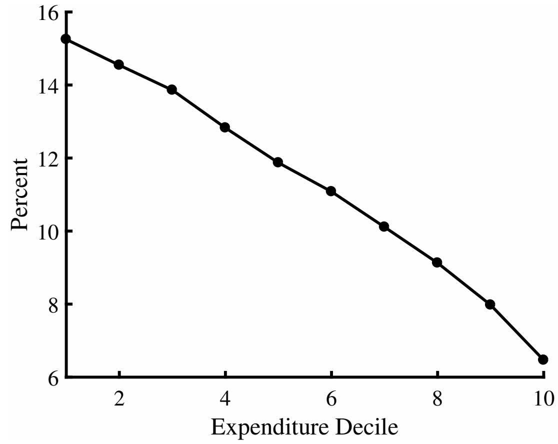
where $\tilde{c}_{i,j,t} = c_{i,j,t}^{\gamma}(e_{i,j,t}^{c} - \bar{e})^{1-\gamma}$. This functional form is separable and homothetic in the consumption-energy composite and labor, implying a constant Frisch elasticity of labor supply regardless of hours worked. We determine β to match the U.S. capital-output ratio of 2.7. We choose χ such that agents spend an average of one third of their time endowment working. Following Conesa et al. (2009), we set the coefficient of relative risk aversion (θ_1) equal to 2 and consistent with Kaplan (2012), we set the Frisch elasticity (θ_2) equal to 0.5.[14]

Previous work notes that the carbon tax by itself may be regressive because lower income individuals devote a larger share of their total consumption expenditures to energy (Metcalf (2007), Hassett et al. (2009)). Figure 1 plots the average energy budget share for each expenditure decile using data from the Consumer Expenditures Survey (CEX) from 1981-2003. Consistent with these previous findings, the average energy budget share falls considerably as average expenditures rise. At the extremes, energy expenditures are over 15 percent of total expenditures for the lowest decile but just over six percent for the highest decile.

[13] We use the Rouwenhorst method to discretize the persistent shock. This method is well-suited for discretizing highly persistent shocks with a small number of states (Kopecky and Suen (2010)).

[14] Peterman (2016) demonstrates that setting the Frisch elasticity at 0.5 is consistent with including hours fluctuations on the intensive margin only.

Figure 1: Energy Budget Share: CEX



Note: Figure displays average energy budget shares by expenditure decile from the 1981-2003 Consumer Expenditures Survey. Energy expenditures include household expenditures on electricity, natural gas, gasoline, and coal and oil in the home. We determine the average energy budget share for each decile conditional on the household's age. Specifically, we first calculate the average energy budget share for each decile within each age bin. Second, for each decile, we calculate a population weighted average across the age bins where the weights are determined by the share of the population in each bin.

Together, the utility parameters $\bar{e}$ and γ determine a household's energy share of total consumption and how this share varies with the household's total consumption expenditures. In particular, the energy share of total consumption expenditures, Ω_t, is

$$\Omega_t = (1-\gamma) + \frac{\gamma p^e \bar{e}}{(1-\gamma)(c_{i,j,t} + p^e e^c_{i,j,t})}. \tag{14}$$

If $\bar{e} = 0$, energy's share of total expenditure equals $1-\gamma$ regardless of the level of an agent's total expenditure. However, if $\bar{e} > 0$, energy's share will decrease with total expenditure. Moreover, higher $\bar{e}$ increases the responsiveness of energy share to changes in total expenditure. We set $\bar{e}$ and γ such that our model matches the data with respect to the average energy share in the population and the percent difference in the energy share of the top and bottom halves of the expenditure distribution ($\Delta\Omega_t = \frac{\Omega_t^{top} - \Omega_t^{bottom}}{\Omega_t^{bottom}} \times 100$). The average energy share in the population is 10.2 percent. Moreover, we target $\Delta\Omega_t = -12.8$ percent.[15]

[15]The actual differential measured in the CEX is 33 percent ($\Delta\Omega = -33$ percent). However, this target needs to be adjusted because the overall differential in total expenditures between the top and bottom halves of the distribution is larger in the data than in our model. In particular, it is 142 percent in the data and

Table 2 reports the value of the moments we target in the model and their corresponding value in the data. Overall, the model fits these targets quite closely.

Table 2: Model Fit

Moment	Target	Model
Energy share: Ω	0.102	0.102
Energy share difference: $\Delta\Omega$	-0.128	-0.128
Hours: H	0.333	0.333
Govt spending to output: $\frac{G}{Y}$	0.155	0.155
Capital to output: $\frac{K}{Y}$	2.7	2.700

3.4 Production

The production technology features a constant elasticity of substitution, ϕ, between a capital-labor composite, $K_t^{\zeta} N_t^{1-\zeta}$, and energy,

$$Y_t = A\left[\left(K_t^{\zeta} N_t^{1-\zeta}\right)^{\frac{\phi-1}{\phi}} + \left(E_t^p\right)^{\frac{\phi-1}{\phi}}\right]^{\frac{\phi}{\phi-1}}. \tag{15}$$

We use 0.5 for the elasticity of substitution between the capital-labor composite and energy, ϕ. This parameter choice is within the range of estimates reported in Van der Werf (2008). We use $\zeta = 0.36$ for capital's share in the capital-labor composite. We calibrate the price of energy, p^e, so that energy's share of production is five percent.

3.5 Government Policies and Tax Functions

We begin our policy experiments in a baseline equilibrium that mimics the U.S. tax code. We follow the quantitative public finance literature and use estimates of the U.S. tax code from Gouveia and Strauss (1994). Gouveia and Strauss (1994) match the U.S. income tax

only 54 percent in our model. The key reason for the smaller differential in total expenditures in our model is that the productivity shocks are assumed to be log normal. This distributional assumption, while standard in the literature, results in our model failing to capture the extreme top tail of the income distribution. Therefore, we adjust for the smaller expenditure variance in our model and target $\Delta\Omega = -12.8$ percent. In particular, we adjust $\Delta\Omega$ so that $\frac{54}{142} = \frac{-12.8}{-33}$.

code to the data using a three parameter functional form:

$$T^h(\tilde{y}^h_{i,j,t}; \Upsilon_0, \Upsilon_1, \Upsilon_2) = \Upsilon_0 \left(\tilde{y}^h_{i,j,t} - \left((\tilde{y}^h_{i,j,t})^{-\Upsilon_1} + \Upsilon_2 \right)^{\frac{-1}{\Upsilon_1}} \right). \tag{16}$$

Parameter Υ_0 governs the average tax rate and parameter Υ_1 controls the progressivity of the tax policy. To ensure that taxes satisfy the budget constraint, we leave parameter Υ_2 free in the baseline. Gouveia and Strauss (1994) estimate that $\Upsilon_0 = 0.258$ and $\Upsilon_1 = 0.768$.

A portion of Social Security benefits are taxable at the labor income tax rate for high income, retired agents. Consistent with U.S. tax law, 85 percent of a retiree's Social Security payments are included as taxable labor income if the retiree's income exceeds 76 percent of average labor income and 50 percent of the benefits are included if the retiree's income is between 76 percent and 56 percent of the average labor income. None of the Social Security benefits are included as taxable labor income if the agent's income is below the 56 percent threshold. The incomes for most retirees are below this 56 percent threshold.[16]

We determine government consumption, G, so that it equals 15.5 percent of output, the average value in the U.S data.[17] We set the tax rate on capital income, τ^k, to 36 percent based on estimates in Kaplan (2012), Nakajima (2010) and Trabandt and Uhlig (2011). To determine the size of the Social Security payments in the baseline steady state, we follow Conesa and Krueger (2006) and assume that retired agents receive 50 percent of the average income of all working individuals

$$S = 0.5 \left(\frac{wN}{\sum_{j<j^r} \Phi(x)} \right). \tag{17}$$

[16]U.S. tax law states that 85 percent of Social Security income is taxable for single households with total income above 34,000 in 2014 dollars and 50 percent is taxable for single households with total income above 25,000 in 2014 dollars. We translate these to thresholds based on the percentage of labor income using data on estimated average earnings in the Annual Statical Supplement from the Social Security Administration (https://www.ssa.gov/policy/docs/statcomps/supplement/2015/highlights.html). See https://www.ssa.gov/planners/taxes.html for a details on U.S. tax law regarding Social Security benefits.

[17]To calculate the empirical value of $\frac{G}{Y}$, we use total government expenditures net of Social Security payments because Social Security is financed by a separate payroll tax in our model. Data on government expenditures, social security benefits and GDP are from the BEA. We use the average value of $\frac{G}{Y}$ from 1998-2007. Additionally, since we assume a small open economy with respect to energy, the model value of GDP (the denominator of $\frac{G}{Y}$) equals the value of total production minus the value of energy imports.

Each period, retirees receive this constant Social Security payment, which is denominated in terms of the numeraire. However, in the simulations, the carbon tax raises the price of the energy-good which reduces the relative price of the numeraire, and thus, decreases the purchasing power of the Social Security payments. In practice, the U.S. government adjusts Social Security payments each year to ensure that the purchasing power remains constant. Consistent with this policy, we adjust the Social Security payment in each simulation to ensure that the retiree can buy the same bundle of energy and non-energy goods as she could in the baseline steady state.[18] We choose the payroll tax, τ_t^s, to ensure that the Social Security system has a balanced budget in every period.

Finally, in the computational experiment, we analyze a carbon tax set at $35 dollars per ton of CO_2. To calibrate the size of the tax in the model, we calculate the empirical value of the tax as a fraction of the price of a fossil energy composite of coal, oil, and natural gas in 2011. We calculate the price of this energy composite averaging over the price of each type of energy in 2011, and weighting by the relative consumption. Similarly, we calculate the carbon emitted from the energy composite by averaging over the carbon intensity of each type of energy in 2011, and weighting by the relative consumption. This process implies that a $35 per ton carbon tax equals 32 percent of our composite fossil energy price.

4 Results

4.1 Computational Experiment

To examine the welfare consequences of a carbon tax, we simulate a baseline economy with no carbon tax and conduct a series of counterfactual simulations in which we impose a constant carbon tax set at $35 per ton of CO_2.[19] We simulate three different policies which vary in how the government rebates the revenue generated from the carbon tax: (1) rebates through

[18]Specifically, Social Security payments in each simulation equal Social Security payments in the baseline times $\frac{c^e(p^e+\tau^c)}{c^e p^e + c}$ where c^e and c are the baseline values of energy and non-energy consumption, respectively.

[19]To solve for the competitive equilibrium in the baseline and under each tax policy, we use an algorithm based on Heer and Maussner (2009). For details on the solution algorithms, see Appendix A.

equal, lump-sum transfers to households, (2) rebates through a reduction in the capital tax rate, and (3) rebates through a reduction in the labor tax rate. To isolate the effect of the carbon tax by itself, we also analyze a fourth case, the no-rebate case, in which the government uses the carbon tax revenue in a non-productive sector (i.e. "throws it into the ocean").[20] Consistent with much of the double-dividend literature, we specifically examine the non-environmental welfare consequences of the carbon tax policies.[21]

4.2 Aggregate welfare effects

Recall, our objective is to examine how the carbon tax policies affect not only the welfare of agents born into the future steady state, but also the welfare of agents alive at the time the carbon tax is adopted. To measure the aggregate welfare impacts, we use the consumption equivalent variation (CEV). In the steady state, the CEV measures the uniform percentage change in an agent's expected consumption that is required to make her indifferent – prior to observing her idiosyncratic ability, productivity, and mortality shocks – between the baseline steady state and the steady state under the carbon tax policy.

In contrast, for cohorts alive when the policy is adopted, the CEV captures the effect of the policy over their remaining lifetimes, and thus, varies based on the cohort's age at the time the policy is adopted. Specifically, to calculate the CEV of the policy for a given age cohort, we compute the uniform percent change in consumption across all agents in the cohort that would be necessary, in every remaining period of their lifetimes, so that the cohort's average expected utility is the same as if they were to live the rest of their lives in the baseline steady state. The aggregate CEV among the living population is the weighted average of the CEVs for each living age cohort. Each cohort's weight is the share of the

[20]Under the different policies, the carbon tax leads to changes in aggregate labor and capital, which affect aggregate tax-revenue from the non-energy tax sources. Thus, in addition to rebating the carbon tax revenue, we adjust the Social Security tax to balance the Social Security budget and we adjust the average labor tax rate to ensure the government budget constraint holds. The progressivity parameters of the labor tax function, Υ_1 and Υ_2, are held constant at their baseline values. Tables 7 and 8 in Appendix B report the tax parameters and the revenue raised from each of the tax instruments in the baseline steady state and in each of the four simulations.

[21]Our results reveal that the reduction in energy use, and therefore, the welfare impacts caused by environmental quality changes, are very similar across the different rebate options. See Appendix C.

expected net present value of the remaining consumption for that cohort relative to the total remaining lifetime consumption for all living cohorts.[22] Therefore, the weights account for the fact that the resources required to fund a one percent increase in a younger cohort's remaining lifetime consumption exceed the resources needed to fund a one percent increase in an older cohort's remaining lifetime consumption.

Table 3 reports the aggregate CEV for agents born into the future steady state and for the living population. A negative CEV indicates that the expected non-environmental welfare is reduced by the carbon tax policy while a positive CEV indicates that the expected non-environmental welfare increases. First, notice that, in the future steady state, the non-environmental welfare costs of the carbon tax policy are lower when the revenue is used to offset a pre-existing distortionay tax, not when the revenue is returned in the form of uniform, lump-sum rebates. Specifically, the CEV under the lump-sum rebate is -1.26 percent compared to only -0.33 percent under the labor tax rebate and 0.29 percent under the capital tax rebate. This pattern is consistent with the weak double-dividend literature.

Table 3: Aggregate Welfare Effects (CEV, percent)

	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Steady State	-6.47	-1.26	0.29	-0.33
Living Population	-4.65	0.26	0.06	-0.63

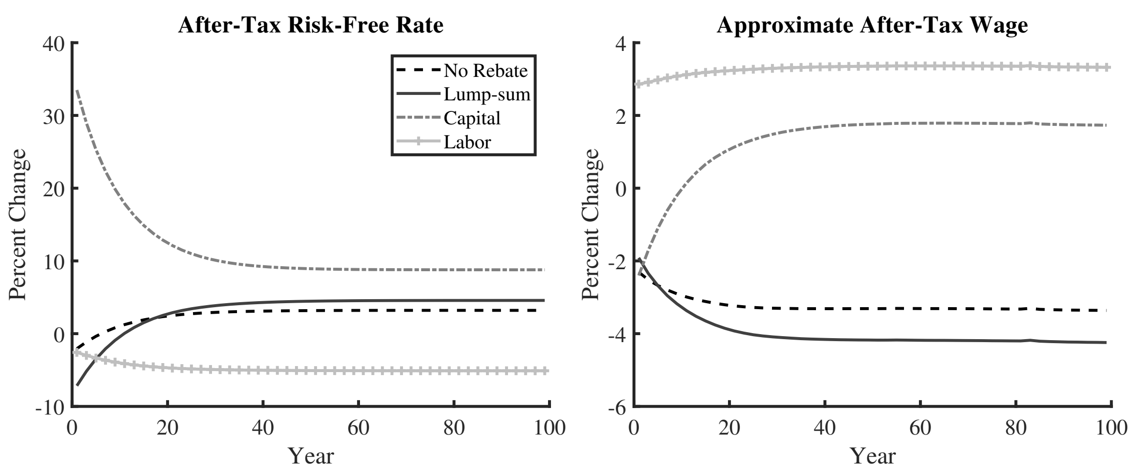
In contrast, for the living population, the pattern is quite different. We find that using carbon tax revenue to reduce the labor or capital tax will be more costly for those alive at the time a carbon tax is implemented. If labor tax revenue is offset, the non-environmental welfare of a living agent will fall, on average, by the equivalent of 0.63 percent of expected future lifetime consumption. This drop in welfare is twice as large as the expected welfare decrease experienced by agents born into the future steady state. Similarly, if capital tax revenue is offset, agents alive at the time of adoption will experience an average welfare increase of only 0.06 percent of expected future lifetime consumption – one fifth as large

[22]We calculate the cohort weights in the steady state.

as the expected welfare increase experienced by agents born into the steady state. In contrast, the lump-sum rebate policy leads to an increase in average welfare among the living population equal to 0.26 percent of expected future lifetime consumption. In the end, the results summarized in Table 3 reveal that, while a policy consistent with the recent Climate Leadership Council proposal – i.e. a carbon tax combined with a uniform lump-sum rebate – will impose relatively large non-environmental welfare costs on agents in the long-run, it may ultimately be the preferred policy among the living population.

To understand why the welfare impacts differ for the living population versus agents born in the future steady state, recall that the long-run impacts reflect the change in a newborn agent's expected lifetime welfare. In contrast, the welfare effect for the living population reflects the average impact over the remainder of the living cohorts' lifetimes. These measures differ largely because the welfare impacts vary over agents' life cycles.[23] For example, if a policy is relatively less costly for older cohorts, then the policy will impose smaller average costs on the living agents compared to those born in the future steady state.

Figure 2: Transition Dynamics: Percent Change From the Baseline



Note: The figures plot the percentage changes in the after-tax returns to capital and labor relative to the baseline steady state values after the policy is adopted. Year zero is the first year under the policy.

To illustrate why the welfare effects vary over the life cycle, Figure 2 first highlights

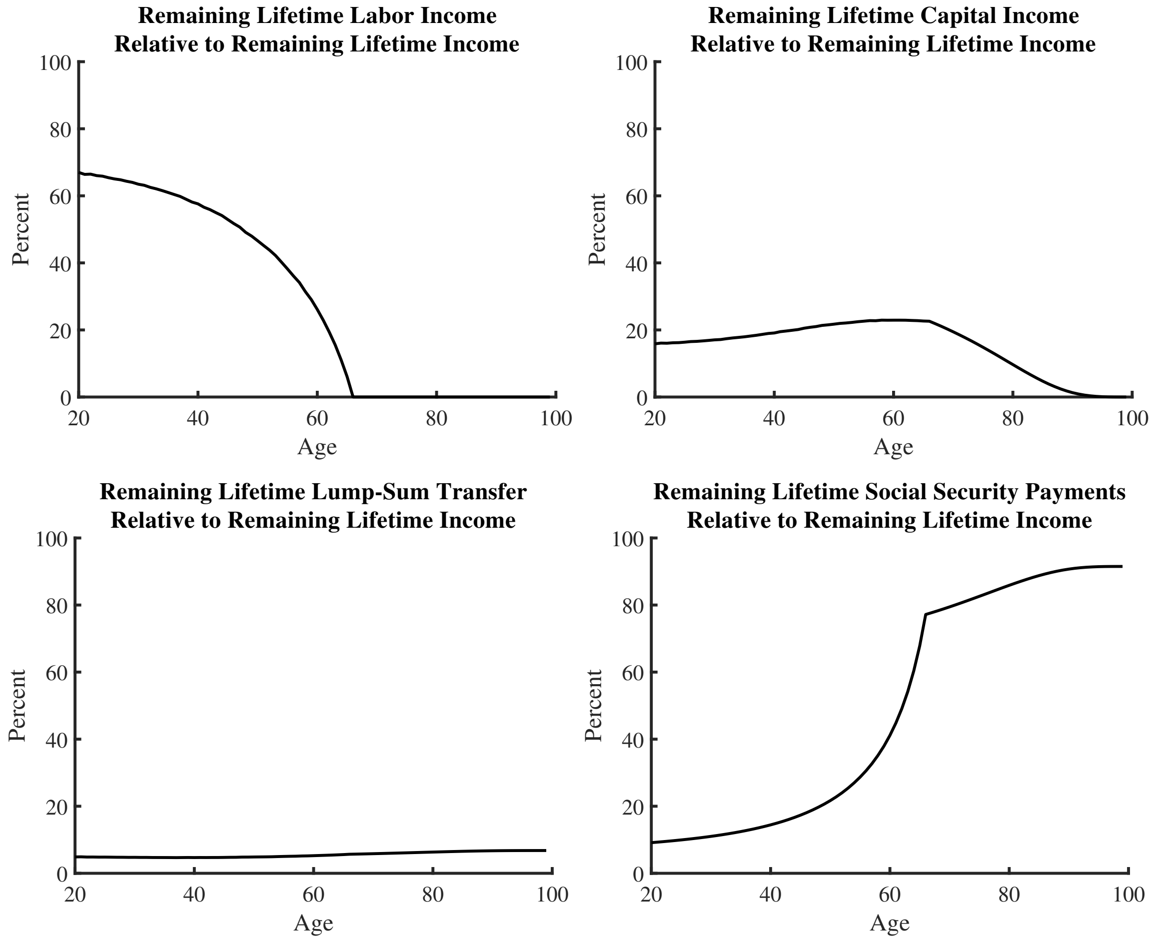
[23]In addition, the effects can vary for newborn agents when the policy is adopted versus agents born in the long-run steady state because the factor prices take time to adjust to their new steady state values.

how the after-tax wage and risk-free rate adjust following the adoption of a tax policy.[24] Ultimately, the welfare consequences of these price changes depend critically on the relative importance of income from capital and labor, which in turn, depend on an agent's age. Figure 3 plots the share of remaining lifetime income from different sources for each age cohort. Intuitively, labor's share of remaining income falls as cohorts age and have fewer working years left. The share of remaining income from capital rises throughout working life as agents accumulate savings and falls as agents deplete their savings during retirement.[25]

[24] Appendix C.2 discusses these factor price movements in more detail.

[25] Similarly, Social Security income's share rises with age. The remaining lifetime income from transfers is relatively stable over the life cycle. Mechanically it rises slightly during the end of life, as the increased mortality risk drives down the remaining lifetime income.

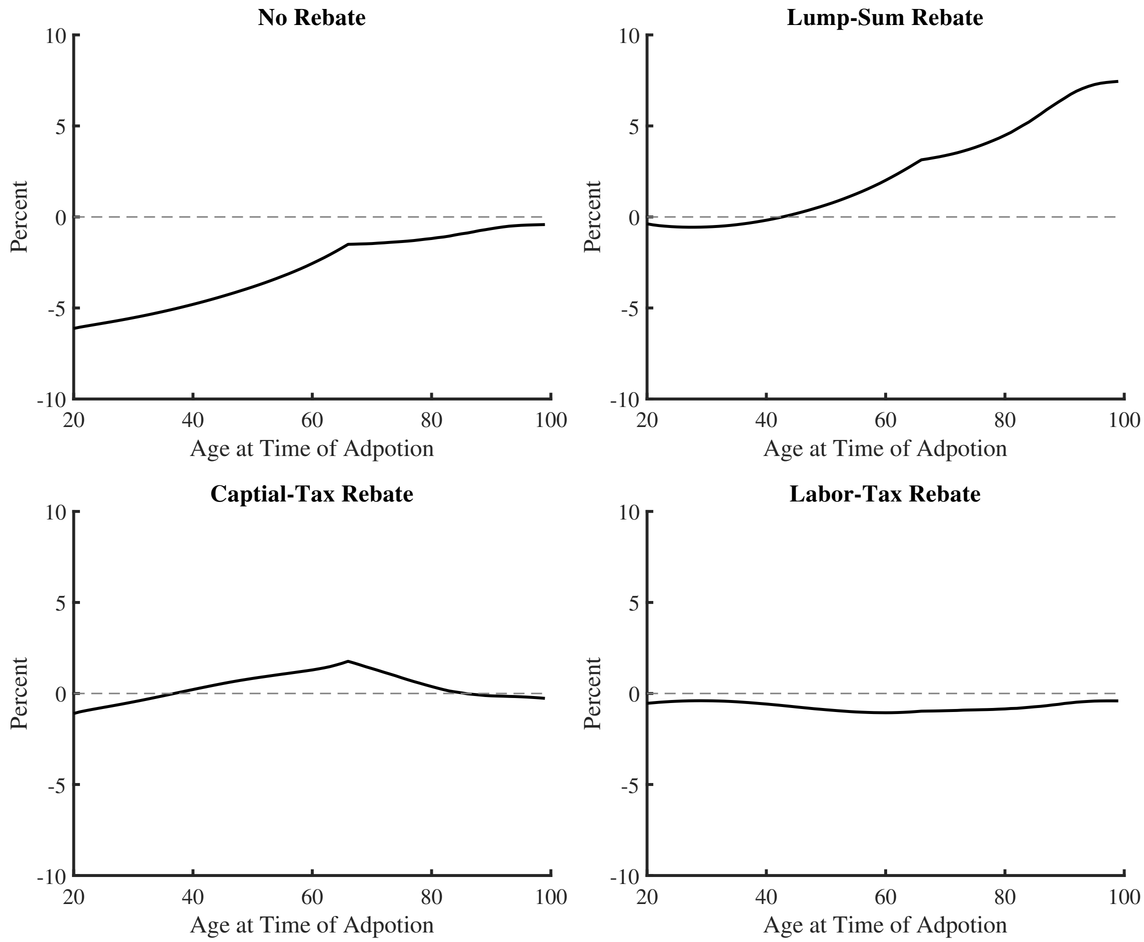
Figure 3: Share of Remaining Lifetime Income by Source



Note: The figure shows the average share of remaining lifetime income from various sources for each age cohort. The figure displays the average share of remaining lifetime income from labor income under the labor-tax rebate policy, from capital income under the capital-tax rebate policy, and from lump-sum reimbursements of carbon tax payments under the lump-sum rebate policy, and from Social Security payments in the baseline. The only source of lifetime income that is not pictured is accidental bequests.

The movements in factor prices, combined with the age-dependent shares of remaining lifetime capital, labor, and transfer income, cause the welfare consequences of a carbon tax policy to vary considerably with the cohort's age when the government introduces the policy. To highlight this variation over the life cycle, Figure 4 plots the average non-environmental welfare effects conditional on the agent's age at the time a carbon tax policy is adopted. The top right panel of Figure 4 illustrates that the lump-sum rebate imposes slight costs on young cohorts while providing substantial gains for the older living cohorts. These older agents receive little to no remaining income from labor, and therefore, do not suffer from the decline in the after-tax wage (see Figure 2). While the older agents are harmed slightly by the small initial decline in the after-tax risk free rate (see Figure 2), this effect is dominated by the welfare gains from the lump-sum transfer. Aggregating across the living cohorts, the lump-sum rebate policy ultimately leads to a sizable increase in expected welfare.

Figure 4: CEV: Agents Alive At Time of Shock



Note: The figure displays the average non-environmental welfare effects of each carbon tax policy for each age cohort at the time the policy is adopted. The welfare impacts are measured as the uniform percent change in expected future consumption in each period needed to make the average welfare for a given cohort the same as in the baseline (i.e., no carbon tax) case. Positive numbers represent a welfare increase as a result of the tax policy change and negative numbers represent a welfare decrease.

Recall, rebating revenue in the form of a reduction in the capital tax leads to an immediate increase in the after-tax risk-free rate and an immediate reduction in the after-tax wage. The bottom left panel of Figure 4 reveals that the large increase in the after-tax risk-free rate increases the non-environmental welfare of agents close to retirement age, the point in the life cycle when capital income accounts for the greatest share of remaining lifetime income (see Figure 3). Among the youngest agents, the benefits from the increase in the after-tax risk-free rate are outweighed by the costs incurred by the reduction in the after-tax wage. Aggregating across all of the living cohorts, non-environmental welfare still increases under the capital tax rebate policy (see Table 3), however, the average welfare gain is smaller than in the long-run steady state.

In contrast to the capital tax rebate, the labor tax rebate causes a fairly stable increase in the after-tax wage and a stable decrease the after-tax risk-free rate. As a result, the line in the labor tax rebate panel (bottom right of Figure 4) exhibits a slight U-shape, as opposed to the hump-shaped line in the capital tax rebate panel. While the increase in the after-tax wage mitigates much of the welfare costs imposed on the youngest agents, older living agents, who receive little to no remaining income from labor, do not receive the same benefits. Overall, the labor tax rebate is more costly among the living population because, unlike in the long-run steady state, the relatively higher welfare costs for middle-aged agents are not offset by the relatively lower costs experienced by younger agents.

4.3 Distribution of welfare effects

The preceding results summarize how the various carbon tax policies, *on average*, affect agents' non-environmental welfare. Under any policy, however, the welfare effects are far from uniform. Table 4 reports the probability that a policy will increase an agent's lifetime, or remaining lifetime, non-environmental welfare relative to the baseline. The results clearly highlight that each revenue-neutral policy will create winners and losers. For example, while the lump-sum rebate policy increases the average welfare of the living population, only 53 percent of the agents alive when the policy is adopted experience welfare gains. The remaining 47 percent of living agents are worse off.

Table 4: Probability of a Welfare Gain (percent)

	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Steady State	0	13	74	43
Living Population	0	53	59	19

The costs, or benefits, created by a given policy will be unevenly distributed for two reasons. First, agents experiencing different productivity shocks, and therefore earning different lifetime incomes, will be affected differently. Second, among the living population, the costs and benefits will differ based on an agent's age when the policy is adopted. A key advantage of our model is that we are able to not only examine how the welfare impacts will be distributed across income groups in the long-run steady state, but also the current population. From a political economy standpoint, it is particularly important to understand how the costs and benefits of alternative policies would be distributed among the living agents. These living agents will be responsible for voting on, or electing policymakers that enact, a carbon tax policy. While it would likely be easier to implement a carbon tax that imposes smaller average welfare costs, or bestows larger average welfare gains, on the living agents, there also may be other important considerations. For example, it may be more difficult to garner support for a carbon tax policy that is regressive and thus imposes relatively larger non-environmental welfare costs on lower income agents. Below, we examine how the welfare impacts vary across income groups in the long-run and among the living population.

4.3.1 Distribution of welfare effects in the steady state

To analyze the long-run distributional impacts, we first calculate the CEV conditional on agents being in a specific income quintile. We determine the income quintiles from agents' realized lifetime expenditures in the baseline case, prior to imposing a carbon tax. Table 5 shows the CEV by income quintile for each tax policy in the long-run steady state. The distributional consequences differ substantially across the policies. If the carbon tax revenues are recycled through uniform lump-sum payments, low income agents are the relative winners. Alternatively, if the revenues are used to reduce one of the pre-existing distortionary taxes, the higher income agents are the relative winners.

Table 5: Steady State Welfare Effects: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV By Quintile (percent)				
Quintile 1	-6.61	0.47	0.03	-1.22
Quintile 2	-6.50	-0.84	0.21	-0.58
Quintile 3	-6.41	-1.64	0.41	-0.16
Quintile 4	-6.35	-2.40	0.51	0.29
Quintile 5	-6.40	-3.25	0.49	0.83
% $\Delta\mathcal{G}$ From Baseline Value of 0.13				
	0.84	-4.39	0.86	2.36

We categorize the policy as regressive if it has higher welfare costs (or smaller welfare benefits) for the lower income quintiles than for the higher income quintiles, and progressive otherwise. To quantify the degree of the progressivity or regressivity of each policy, we calculate the percent change in the Gini coefficient for lifetime non-environmental welfare across the original baseline and the new steady state. We define the Gini coefficient, $\mathcal{G}$, as

$$\mathcal{G} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}|x_i - x_j|}{2N^2\bar{x}}, \tag{18}$$

where x_i represents lifetime welfare of agent i, $\bar{x}$ is the mean of lifetime welfare, and N is the total number of agents in the economy. The Gini coefficient ranges between zero and one with zero implying perfect equality and one implying perfect inequality. Thus, a positive percent change in the Gini coefficient implies that the carbon tax policy is regressive (i.e. it increases inequality) while a negative percent change implies that the policy is progressive.

Referring to the bottom row of Table 5, the no rebate case demonstrates that, in the long-run, the carbon-tax by itself results in an increase in the Gini coefficient of 0.84 percent.[26]

[26] The value of the Gini coefficient in the baseline is 0.13. This is much lower than the Gini coefficient for income in the U.S. data, implying that we have less inequality in our model than the data. As numerous studies have noted (e.g., Guvenen et al. (2015)) a substantial portion of the income inequality in the U.S. comes from the top one percent, which the log-normal distribution for labor-productivity does not capture.

In large part, the carbon tax by itself is regressive because lower income agents devote larger fractions of their budgets to energy consumption. Therefore, a larger portion of lower income agents' income is absorbed by the carbon tax, making them worse off.[27]

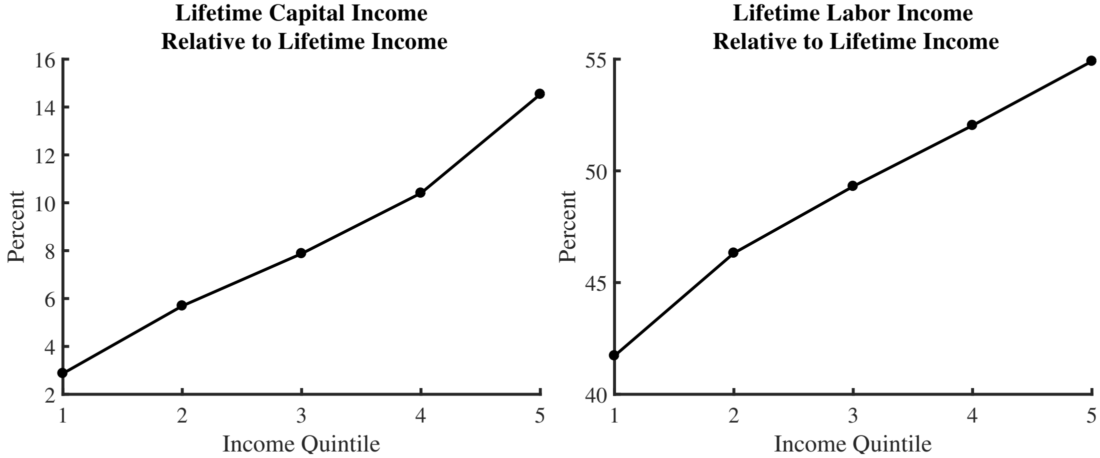
The way in which the government rebates carbon tax revenue can either exacerbate or mitigate the regressivity of the carbon tax policy. Under the uniform lump-sum rebate policy, the Gini coefficient falls by 4.38 percent in the long-run. By rebating the revenue through equal, lump-sum transfers, the government is able to fully reverse the inherent regressiveness of the carbon tax, making the revenue-neutral carbon tax policy progressive.

Rebating the carbon tax revenue by reducing the capital tax rate, on the other hand, does not meaningfully affect the regressivity of the carbon tax policy – the long-run Gini coefficient increases by 0.86 percent under the capital tax rebate policy, similar to the 0.84 percent increase under the no-rebate case. This stems from the fact that reducing the capital tax rate causes two, offsetting outcomes. First, as the left panel of Figure 5 highlights, agents with higher lifetime income receive a larger share from capital income.[28] As a result, higher income agents receive a larger direct benefit from the reduction in the capital tax, causing a regressive effect. This is ultimately offset, however, by the fact that the capital tax rebate also leads to an increase in the size of the economy and in accidental bequests, which have positive wealth effects across all income quintiles (see Appendix C for more details). The concavity of the utility function implies that the welfare gains from these wealth effects are larger for the lower income quintiles, mitigating the regressive effects from the capital tax rebate.

[27]It is important to note that, in our model, the subsistence level of energy consumption is non-binding for all households (i.e. household energy consumption exceeds $\bar{e}$ for all homes in all periods). In a subsequent robustness check, we also re-examine the results assuming that $\bar{e} = 0$.

[28]Note, transfers and social security account for a smaller share of total income among the higher income quintiles. As a result, labor and capital income shares both increase across the income quintiles.

Figure 5: Capital and Labor Income as a Fraction of Total Lifetime Income



Note: The left panel displays the share of lifetime income accounted for by capital income under the carbon tax policy that uses carbon revenues to reduce capital taxes. The right panel displays the share of lifetime income account for by labor income under the carbon tax policy that uses carbon revenues to reduce the labor tax rate. In both figures, the average income shares are displayed for agents in each income quintile. Agents are assigned to specific income quintiles based on their realized lifetime expenditures in the baseline case, prior to imposing a carbon tax. Note, transfers account for a smaller share of total income among the higher income quintiles. As a result, labor and capital income shares both increase across the income quintiles.

The regressivity of the labor tax rebate policy is more pronounced than the carbon tax by itself – the long-run Gini coefficient increases by 2.36 percent. The right panel of Figure 5 highlights that agents with high lifetime income receive a larger share of their total income from labor. As a result, a reduction in the labor tax rate provides sizable benefits to agents in the high income quintiles and smaller benefits to agents in the lower income quintiles.

4.3.2 Distribution of welfare effects for the living population

Just as the aggregate welfare effects can differ over time, the distributional impacts may also be quite different across the current and long-run populations. To examine the distributional impacts among the living agents, Table 6 reports the CEV by income quintile for each tax policy for the living agents. In addition, we calculate the percent change in the Gini coefficient for the living population compared to the baseline in which no carbon tax is adopted. To calculate the Gini coefficient among the living population, we first calculate the

Gini coefficient for each age cohort at the time of adoption. For example, for agents that are 25 when the policy is enacted, we calculate the Gini coefficients in both the baseline and the transition from expected remaining lifetime welfare starting at age 25.[29] We then take the weighted average of the Gini coefficients across cohorts to calculate the aggregate Gini coefficient for the living population in the baseline as well as under each carbon tax policy.[30] The percent change in the Gini coefficient under each policy is reported at the bottom of Table 6.

Table 6: Welfare Effects For the Living Population: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV (percent)				
Quintile 1	-4.77	2.10	-0.86	-1.18
Quintile 2	-4.67	0.60	-0.20	-0.72
Quintile 3	-4.61	-0.22	0.33	-0.48
Quintile 4	-4.56	-0.99	0.77	-0.23
Quintile 5	-4.50	-1.85	1.29	0.00
% $\Delta\mathcal{G}$ From Baseline Value of 0.15				
	0.48	-4.18	2.49	1.19

Just as we found in the steady state, within the living population, the uniform lump-sum rebate policy is progressive and the capital and labor tax rebate policies are regressive. However, when we compare the degree of the regressivity, as measured by the percent changes in the Gini coefficients (bottom rows of Table 5 and Table 6), we see some meaningful differences. In particular, within the living population, the capital tax rebate is substantially more regressive while the labor tax rebate is considerably less regressive.

To understand why the distributional impacts differ over time, particularly for the labor and capital tax rebate policies, Figure 6 plots the percent change in the Gini coefficient

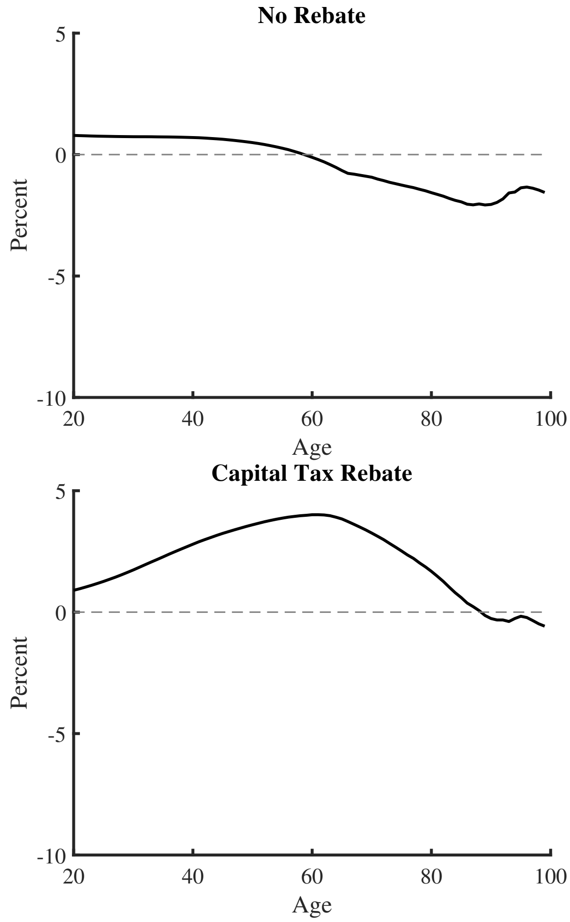
[29]For a comparison of of the Gini coefficient for each age cohort in the baseline, see Figure 10 in Appendix C.

[30]Note that the baseline value of the Gini coefficient among the living agents varies slightly from the steady state baseline value (0.13 vs. 0.15) because it is a weighted average of the Gini coefficients for the living cohorts' remaining life cycles in the baseline.

for the different age groups. Under the labor tax rebate, the percent change in the Gini coefficient decreases steadily with age, causing the labor-tax rebate to be more progressive among the living agents. This pattern is explained by the factor returns. The after-tax wage increases immediately, providing the largest benefit to the youngest, highest lifetime income agents who experience large, positive productivity shocks. In contrast, the after-tax risk-free rate falls, imposing the largest immediate costs on older, wealthy agents who have accrued the largest amount of savings. As a result, aggregating across the living cohorts, the labor tax rebate policy is less regressive compared to the future steady state distributional impact.

Under the capital tax rebate, the percent change in the Gini coefficient is positive across nearly every cohort alive at the time the policy is adopted. The increase in regressivity is the most pronounced within the cohorts that are nearing the age of retirement – the cohorts that have the highest average, and highest variance, in capital savings. In contrast, at the time the policy is implemented, younger cohorts have accrued very little capital savings. By the time these younger cohorts have progressed through their working lives and accrued greater savings, the after-tax risk-free rate – which experiences a dramatic increase immediately after the policy is adopted – will have dropped towards the new steady state level. Therefore, the regressive effects of the increase in the after-tax returns to capital will be less dramatic among the younger cohorts. Given that the middle-aged cohorts have already lived beyond the point when the policy would be relatively less regressive, the capital tax rebate policy ends up being much more regressive within the living population as opposed to the future steady state.

Figure 6: Percent Change in the Gini Coefficient Between Baseline and Transition



Note: The figures display the distributional impacts each carbon tax policy will have among agents in specific age cohorts based on the agents' age at the time the policy is adopted. The distributional impacts are measured by the percent change in the within-age cohort Gini coefficient under the specific carbon tax policy relative to the baseline case. The Gini coefficient is calculated from the lifetime welfare (see equation (18)). An increase in the Gini coefficient (positive value on the figure) implies that the carbon tax policy increases inequality relative to the baseline (no carbon tax) case.

4.4 Robustness

4.4.1 Endogenous Energy Production

Thus far, we have assumed that energy could be purchased from a world market at a constant price. Under this assumption, the energy price does not endogenously respond to the adoption of a domestic carbon tax. In reality, if the U.S. were to adopt a carbon tax, total demand for fossil energy would decline, and the domestic and world energy prices would decrease. Ultimately, the decline in the energy price would likely be small. Therefore, assuming an exogenous energy price likely does not represent an extreme simplification. Nonetheless, we alter our modeling assumptions to examine whether the key findings from the preceding analysis are driven by the imposition of an exogenous world energy price.

We allow the energy price to endogenously respond to the adoption of a carbon tax and analyze a two-sector model in which both the final good and energy are only produced domestically. Assuming that all energy is produced and sold domestically will dramatically overstate the endogenous decline in the energy price caused by the adoption of a carbon tax. Therefore, we view our previous model as our preferred specification. However we find that the pattern of results from the model presented in Section 4 are effectively unchanged with the inclusion of an endogenous energy price (see Appendix D for more details).

4.4.2 Subsistence Energy Consumption

To ensure that our model captured the observed negative relationship between income and expenditure shares, we specified a non-homothetic utility function. In particular, we assumed that agents must consume a minimum amount of energy, $\bar{e}$, and that the agents receive no utility from this subsistence level of energy consumption. While previous studies have pointed to the negative relationship between income and energy expenditure shares as a key driver of the distributional impacts of carbon taxes (e.g., Metcalf (2007), Hassett et al. (2009)), no previous OLG models have modeled this relationship. To provide insight into how non-homotheticity affects the results presented in Section 4, we consider the special case where $\bar{e} = 0$ and, thus, the energy expenditure share is constant across income groups.

Overall we find that assuming homotheticity does not meaningfully alter the average welfare impacts of the carbon tax policies simulated or the comparison of the distribution of welfare impacts between the living population and the future steady state. However, compared to the earlier results from the case where $\bar{e} > 0$ (see Tables 5 and 6), each policy is now less regressive (or more progressive). Effectively, given that the energy expenditure share is no longer larger among the lower income groups, the direct effect of the carbon tax is no longer regressive (see Appendix D for more details).

5 Conclusion

Imposing a carbon tax would affect welfare not only through environmental channels, but also through non-environmental channels by causing large, general equilibrium impacts throughout the economy. In addition, a carbon tax would generate a substantial stream of government revenue. Policymakers often advocate returning carbon tax revenue to individuals in the form of lump-sum transfers (e.g., the recent proposal from the Climate Leadership Council). However, previous studies in the environmental and public economics literature highlight that, in the long-run, it is far more efficient to use carbon tax revenues to reduce pre-existing distortionary taxes as opposed to returning the revenue in the form of lump-sum payments. While the existing research illustrates the impact revenue-neutral carbon tax policies can have on agents born in the future long-run steady state, there is little understanding of how agents living during the transition to the new steady state will be affected.

Using a quantitative, overlapping generations model that builds on the macro public finance literature, we find that the non-environmental welfare effects of revenue-neutral carbon tax policies differ substantially between agents who are alive when the policy is enacted and agents who are born into the new, long-run steady state. In particular, among the policies we examine, we find that, in the long-run, returning carbon tax revenues through uniform, lump-sum rebates causes the largest reduction in expected non-environmental welfare. In contrast, among the agents alive when a carbon tax is imposed, the lump-sum rebate policy not only results in the largest increase in average welfare, but also distributes these gains very progressively and in a way such that over half of the living agents are better off.

The results presented in this paper demonstrate that estimates of the non-environmental welfare costs of carbon tax policies that are based solely on the long-run, steady state outcomes often miss-represent the near-term costs and distributional consequences of the policies. As we transition to a new steady state, a revenue-neutral carbon tax policy has the potential to impose sizable costs that fall disproportionately on specific segments of the current population. Understanding these transitional effects is especially important for the political feasibility of the policy, since the agents who vote on – or elect policymakers that enact – a carbon tax are ultimately those that experience its near-term consequences. Thus, when designing climate policies, policymakers must pay careful attention to not only the long-run outcomes, but also the transitional welfare effects of the policy.

Our analysis focused on three of the most widely discussed rebate options for carbon tax revenue in the economics literature: capital tax rebates, labor tax rebates, and rebates through uniform lump-sum transfers. We found that within this set of policy instruments, the policy options that were most preferred in the long-run steady state were not the most preferred options over the transition. Future work could extend the current analysis to consider how alternative rebate policies could potentially alleviate the large welfare costs imposed on the current generations without reducing the long-run welfare gains of the policy. Possible options to explore include dynamically varying policies that combine rebate mechanisms in different proportions over time as well as changes in the progressivity of the existing distortionary taxes.

References

Baker, James A., Martin Feldstein, Ted Halstead, N. Gregory Mankiw, Henry M. Paulson Jr., George P. Shultz, Thomas Stephenson, and Rob Walton, "The Conservative Case for Carbon Dividends," Technical Report, Climate Leadership Council February 2017.

Barrage, Lint, "Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy," 2016.

Baumol, William J. and Wallce E. Oates, *The Theory of Environmental Policy*, Cambridge University Press, 1988.

Bell, Felicitie and Michael Miller, "Life Tables for the United States Social Security Area 1900-2100," *Actuarial Study 120, Office of the Chief Actuary, Social Security Administration*, 2002.

Bovenberg, Lans, "Green Tax Reforms and the Double Dividend: An Updated Reader's Guide," *International Tax and Public Finance*, 1999, *6(3)*, 421–443.

Carbone, Jared, Richard Morgenstern, Roberton Williams III, and Dallas Burtraw, "Deficit Reduction and Carbon Taxes: Budgetary, Economic, and Distributional Impacts," *Considering a Carbon Tax: A Publication Series from RFF's Center for Climate and Electricity Policy*, 2013.

Castaneda, Ana, Javier Diaz-Gimenez, and Jose-Victor Rios-Rull, "Accounting for the US Earnings and Wealth Inequality," *Journal of Political Economy*, 2003, *111*, 818–857.

CBO, "Reducing the Deficit: Spending and Revenue Options," Technical Report, United States Congressional Budget Office March 2011.

Chiroleu-Assouline, Mireille and Mouez Fodha, "From regressive pollution taxes to progressive environmental tax reforms," *European Economic Review*, 2014, *69)*, 126–142.

Conesa, Juan Carlos and Dirk Krueger, "On the Optimal Progressivity of the Income Tax Code," *Journal of Monetary Economics*, 2006, *53*, 1425–1450.

_ , Sagiri Kitao, and Dirk Krueger, "Taxing Capital? Not a Bad Idea After All!," *American Economic Review*, 2009, *99(1)*, 25–38.

Dales, John H., *Pollution, Property, and Prices: An Essay in Policy-Making and Economics*, Vol. 83, University of Toronto Press, 1968.

de Mooij, Ruud and Lans Bovenberg, "Environmental Taxes, International Capital Mobility and Inefficient Tax Systems: Tax Burden versus Tax Shifting," *International Tax and Public Finance*, 1998, *5(1)*, 7–39.

der Werf, Edwin Van, "Production functions for climate policy modeling: an empirical analysis," *Energy Economics*, 2008, *30(6)*, 2964–2979.

Dinan, Terry and Diane Rogers, "Distributional Effects of Carbon Allowance Trading: How Government Decisions Determine Winners and Losers," *National Tax Journal*, 2002, *LV*, 199–222.

Domeij, David and Jonathan Heathcote, "On The Distributional Effects Of Reducing Capital Taxes*," *International Economic Review*, 2004, *45* (2), 523–554.

Dyrda, Sebastian, Marcelo Pedroni et al., "Optimal fiscal policy in a model with uninsurable idiosyncratic shocks," Technical Report 2015.

Fehr, Hans and Fabian Kindermann, "Taxing capital along the transition – Not a bad idea after all?," *Journal of Economic Dynamics and Control*, 2015, *51*, 64–77.

Fullerton, Don and Garth Heutal, "The general equilibrium incidence of environmental taxes," *Journal of Public Economics*, 2007, *91*, 571–591.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski, "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica*, 2014, *82* (1), 41–88.

Goulder, Lawrence, "Environmental Taxation and the Double Dividend: A Reader's Guide," *International Tax and Public Finance*, 1995, *2(2).*

Gouveia, Miguel and Robert Strauss, "Effective Federal Individual Income Tax Functions: An Exploratory Empirical Analysis," *National Tax Journal*, 1994, *47(2)*, 317–339.

Guvenen, Fatih, Fatih Karahan, Serdar Ozkan, and Jae Song, "What Do Data on Millions of U.S. Workers Reveal About Life-cycle Earnings Risk?," *working paper*, 2015.

Hassett, Kevin, Aparna Mathur, and Gilbert Metcalf, "The Incidence of a U.S. Carbon Tax: A Lifetime and Regional Analysis," *Energy Journal*, 2009, *30(2)*, 157–180.

Heer, Burkhard and Alfred Maussner, *Dynamic General Equilibrium Modeling: Computational Methods and Applications*, Springer Science & Business Media, 2009.

Horowitz, John, Julie-Anne Cronin, Hannah Hawkins, Laura Konda, and Alex Yuskavage, "Methodology for Analyzing a Carbon Tax," Technical Report, United States Department of the Treasury, Office of Tax Analysis, Washington D.C. 2017. Working Paper 115.

IAWG, "Interagency Working Group – Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866," 2013.

Kaplan, Greg, "Inequality and the Lifecycle," *Quantitative Economics*, 2012, *3(3)*, 471–525.

Kopecky, Karen A and Richard MH Suen, "Finite state Markov-chain approximations to highly persistent processes," *Review of Economic Dynamics*, 2010, *13* (3), 701–714.

Leach, Andrew J, "The welfare implications of climate change policy," *Journal of Environmental Economics and Management*, 2009, *57* (2), 151–165.

Metcalf, Gilbert, "A Proposal for a US Carbon Tax Swap: An Equitable Tax Reform to Address Global Climate Change," *Hamilton Project, Brookings Institute*, 2007.

Montgomery, David W., "Markets in Licenses and Efficient Pollution Control Programs," *Journal of Economic Theory*, 1972, *5* (3), 395–418.

Nakajima, Makoto, "Optimal Capital Income Taxation with Housing," *working paper*, 2010.

Parry, Ian, "Are Emissions Permits Regressive?," *Journal of Environmental Economics and Management*, 2004, *47(2)*, 364–387.

_ **and Roberton Williams**, "What Are the Costs of Meeting Distributional Objectives for Climate Policy?," *B.E. Journal of Economic Analysis & Policy*, 2010, *10(2).*

Peterman, William, "Determining the Motives for a Positive Optimal Tax on Capital," *Journal of Economic Dynamics and Control*, 2013, *37(1)*, 265–295.

Peterman, William B., "Reconciling Micro and Macro Estimates of the Frisch Labor Supply Elasticity," *Economic Inquiry*, 2016, *54* (1), 100–120.

Pigou, Arthur C., "The Economics of Welfare," *London: Macnillam*, 1920.

Pizer, William A and Steven Sexton, "Distributional Impacts of Energy Taxes," Technical Report, National Bureau of Economic Research, Working Paper 23318 2017.

Rausch, Sebastian, "Fiscal consolidation and climate policy: An overlapping generations perspective," *Energy Economics*, 2013, *40*, S134–S148.

Trabandt, Mathias and Harald Uhlig, "The Laffer curve revisited," *Journal of Monetary Economics*, 2011, *58*, 305–327.

Williams, Roberton, Hal Gordon, Dallas Burtraw, and Jared Carbone, "The Initial Incidence of a Carbon Tax Across Income Groups," *National Tax Journal*, 2015, *68(1)*, 195–214.

The Distributional Effects of a Carbon Tax on Current and Future Generations: Online Appendices

Stephie Fried, Kevin Novan, William B. Peterman

A Solution Algorithm

To determine the competitive equilibrium for each tax policy, we use a modified algorithm based on Heer and Maussner's algorithm 6.2.2 for computing a stationary equilibrium for the overlapping generations model.[31] The algorithm consists of the following steps:

1. Make initial guesses of the steady state values of the aggregate variables (capital, labor, accidental bequests, and wage earnings), market clearing income tax (Υ_2 in the steady state without an environmental tax and Υ_0 in the other steady states), and the Social Security benefits.

2. Use equation (7) to solve for aggregate energy.

3. Solve for the factor prices using the equations (5) and (6). Solve for the Social Security tax rates using equation (8).

4. Compute the value function for agents on the state space of ability, idiosyncratic shocks, savings and age using backward induction.[32]

5. Simulate the life cycles of 3,000 agents to calculate the distribution of agents across the state space. Each agent enters the model with zero capital and faces its own unique set of idiosyncratic shocks. We generate the individual shocks that are consistent with our labor productivity process by drawing from the distributions in equation (1). Given these shocks and the policy functions for labor, consumption, and savings (from the value function in step 4), we iterate forward to solve for the time paths of the choice variables for each agent over her life cycle.

6. Compute the income tax rate that clears the government budget constraint, equation (10). Integrate over the distribution of agents to calculate aggregate capital, labor, and accidental bequests using equations (9) and (11). Calculate average labor earnings and Social Security benefits.

[31] See Heer and Maussner (2009).

[32] We discretize the savings grid and interpolate the value function between savings grid points.

7. Check if the tax rates and the aggregate variables calculated in step 6 are within the tolerance of guesses in step 1. If the difference is larger than the tolerance, then update the guesses in step 1 using a weighted average of the previous guess and the new values from step 6 and return to step 1.

Once we have calculated the initial and final steady states using the previous algorithm, we use a shooting algorithm based on Heer and Maussner's algorithm 7.1.1 to compute the transition path between these steady states:

1. Set the number of transition periods to 100.[33]

2. Guess a time path for the transition of the aggregate variables (capital, labor, accidental bequests, and wage earnings) and the market clearing labor income tax (Υ_0).

3. Using equations (5), (6), (7), and (8) solve for factor prices, energy, and Social Security tax rates.

4. Compute the value function for t=T-1 from the factor prices and tax rates calculated in step 3 and the tax rates guessed in step 2. Use the value function in the final steady state as the value function in period $t = T$. Continue to iterate backwards in time, $t = T - 2$, $t = T - 3$, and so on.

5. Use the distribution of agents in the initial steady state to initialize the distribution of agents across the state space for time period $t = 1$.

6. In each period $t > 1$ of the transition, simulate the life cycles of 3,000 agents to calculate the distribution of agents across the state space in that period. Each agent enters the model with zero capital and faces its own unique set of idiosyncratic shocks. We generate the individual shocks that are consistent with our labor productivity process by drawing from the distributions in equation (1). Given these shocks and the policy functions for labor, consumption, and savings (from the value function in step 4), and

[33] We check whether this is a sufficient number of periods and find that the transition occurs in substantially less than 100 periods.

the time paths for the factor prices (from step 3) we iterate forward to solve for the time paths of the choice variables for each agent over her life cycle.

7. Compute the labor tax rate that clears the market in each period of the transition. Integrate the individual values of capital and labor over the distribution of agents in each time period of the transition to compute the time paths of the aggregate values of capital and labor.

8. Check if the labor tax rate and the aggregate variables calculated in step 7 are within the tolerance of the guesses for each period from step 2. If the difference is larger than the tolerance, update the guesses in each period using a weighted average of the previous guesses and the new values solved for in step 7. Return to step 3.

B Computational experiment details

As discussed in Section 4.1, the carbon tax leads to changes in aggregate labor and capital supplies, which affect aggregate tax-revenue from the non-energy tax sources. Thus, in addition to rebating the revenue from the carbon tax, we need to adjust the Social Security tax to ensure that the Social Security budget balances, and we need to alter either the capital or labor tax to ensure that the government's budget constraint clears. We choose to clear the government budget constraint by adjusting the average labor tax rate but hold the general progressivity of the labor tax policy consistent with the policy in the baseline model.[34] Tables 7 and 8 report the tax parameters and the revenue raised from each of the tax instruments in the baseline steady state and in each of the four simulations. Note that in the no-rebate simulation, total tax revenue exceeds the level of government spending, G, because the government throws the carbon-tax revenue into the ocean.

[34] In particular, to clear the government budget constraint, after rebating the revenue from the carbon tax, we alter Υ_0 and hold τ^k, Υ_1 and Υ_2 fixed. This approach minimizes changes in the progressivity of the labor-tax function.

Table 7: Tax Parameters

		Carbon Tax			
	Baseline	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Labor tax: Υ_0	0.26	0.26	0.27	0.26	0.19
Labor tax: Υ_1	0.77	0.77	0.77	0.77	0.77
Labor tax: Υ_2	1.75	1.75	1.75	1.75	1.75
Capital tax: τ^k	0.36	0.36	0.36	0.13	0.36
Payroll tax: τ^s	0.11	0.11	0.12	0.11	0.11
Carbon tax: $\frac{\tau^c}{p^e}$	0.00	0.33	0.33	0.33	0.33

Table 8: Percent of Government Revenue

		Carbon Tax			
	Baseline	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Labor Tax	68.45	68.29	68.98	69.93	49.69
Capital Tax	31.79	31.94	31.27	10.08	30.56
Carbon Tax	0.00	19.52	19.36	20.18	19.92
Lump-Sum Rebate	-	-	-19.36	-	-

C Additional Results

C.1 Steady state

To further understand the responses to the various tax policies, Table 9 reports the resulting steady state macroeconomic aggregates and factor prices. The first column reports the baseline values of the aggregate variables and the remaining columns report the percentage changes relative to the baseline values in each of the simulations.[35] The results reveal first that, regardless of how the government uses the carbon tax revenue, the increase in the cost of energy will induce reductions in energy consumption. Across the three revenue-neutral policies simulated, total energy consumption ($E^p + E^c$) in the steady state falls by 13.21 percent to 16.74 percent.

[35]We define the net (after-tax) efficiency wage as $(1 - \bar{\tau}^l)w$ where $\bar{\tau}^l$ is the average labor-tax rate.

Table 9: Steady State Aggregates

		Percent Change From Baseline: Carbon Tax			
	Baseline	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Macro Aggregates					
Output: Y	0.82	-0.66	-3.50	2.60	0.16
Efficiency Hours: N	0.52	1.73	-0.89	-0.12	0.79
Capital: K	2.09	-2.62	-5.88	10.04	1.30
Consumption: C	0.42	-2.40	-0.66	3.07	2.68
Energy					
Prod. Energy: E^p	16.33	-13.76	-16.23	-10.93	-13.04
Con. Energy: $E^c - \bar{E}$	12.31	-26.40	-25.08	-22.27	-22.57
Tot. Energy: $E^p + E^c$	34.27	-16.03	-16.74	-13.21	-14.32
Prices and Transfers					
Efficiency Wage: w	0.95	-3.13	-3.41	1.90	-1.41
Risk-Free Rate: r	0.05	3.19	4.57	-20.00	-5.10
Net Efficiency Wage: $(1-\bar{\tau}^l)w$	0.81	-3.30	-4.19	1.79	3.36
Net Risk-Free Rate: $(1-\tau^k)r$	0.03	3.19	4.57	8.78	-5.10
Transfers: $T^a + T^c$	0.03	-3.63	76.96	11.49	2.02

Of course, the carbon tax affects far more than firms' and households' demand for energy. For example, by reducing the firms' use of energy, the carbon tax will lower the marginal products of both capital and labor – leading to a decrease in the demand for both inputs. On the household side, the carbon tax raises the relative price of the consumption-energy composite, $\tilde{c}$. This price change increases the cost of retirement, which raises agents' incentivizes to save. In addition, the price change also distorts the household's intratemporal allocation between $\tilde{c}$ and leisure, generating both income and substitution effects. The income effect pushes households to increase their hours because the higher cost of $\tilde{c}$ makes them relatively poorer. Conversely, the substitution effect pushes households to reduce their hours and substitute leisure for consumption since the cost of $\tilde{c}$ relative to leisure is higher.

The general equilibrium interactions among these various distortions lead to changes in the long-run equilibrium aggregates and factor prices. Importantly, the results presented in Table 9 reveal that the government's choice of how to rebate the carbon tax revenue greatly determines how the steady state aggregates change, and therefore, how agents' expected non-environmental welfare is affected. Rebating the carbon revenue through a reduction in the capital tax rate leads to an increase in both the steady state after-tax risk-free rate and aggregate capital. While agents respond to the lower capital tax by shifting hours to earlier in their life cycle, the total hours worked remains largely unchanged.[36] Overall, this leads to a small increase in the steady state wage rate.

Under the labor tax rebate policy, the after-tax wage increases, leading agents to increase their hours slightly in the steady state. With the increased labor earnings, agents increase savings. The increase in capital, combined with the decline in the firm's use of energy, ultimately outweigh the impact of the small increase in hours, leading to a reduction in the marginal product of capital (i.e. the risk-free rate).

Under the lump-sum rebate policy, the steady state level of capital falls substantially because agents do not have to save as much for retirement.[37] Similarly, agents work slightly fewer hours primarily because they don't need to put as much away for retirement. Ultimately, the larger reduction in capital outweighs the small reduction in hours, leading to an increase in the risk-free rate.

The results in Table 9 reveal the impact of each carbon tax policy on the steady state values of aggregate capital, labor, consumption, and energy usage. To examine how an individual agent's capital savings, hours worked, consumption, and energy consumption vary over the life cycle in the steady state, Figure 7 plots the average life cycle profile of each variable in the baseline and under each of the policies. To compare the impact of each policy, Figure 8 displays the percent change in the life-cycle profiles induced by each policy.

Savings are lower in every period of the life cycle under the lump-sum rebate (relative to the baseline) because the lump-sum rebate reduces agents' need to save for retirement. In contrast, savings are higher in every period of the life cycle under the capital-tax rebate because the rise in the after-tax risk-free rate increases the return to savings. Additionally,

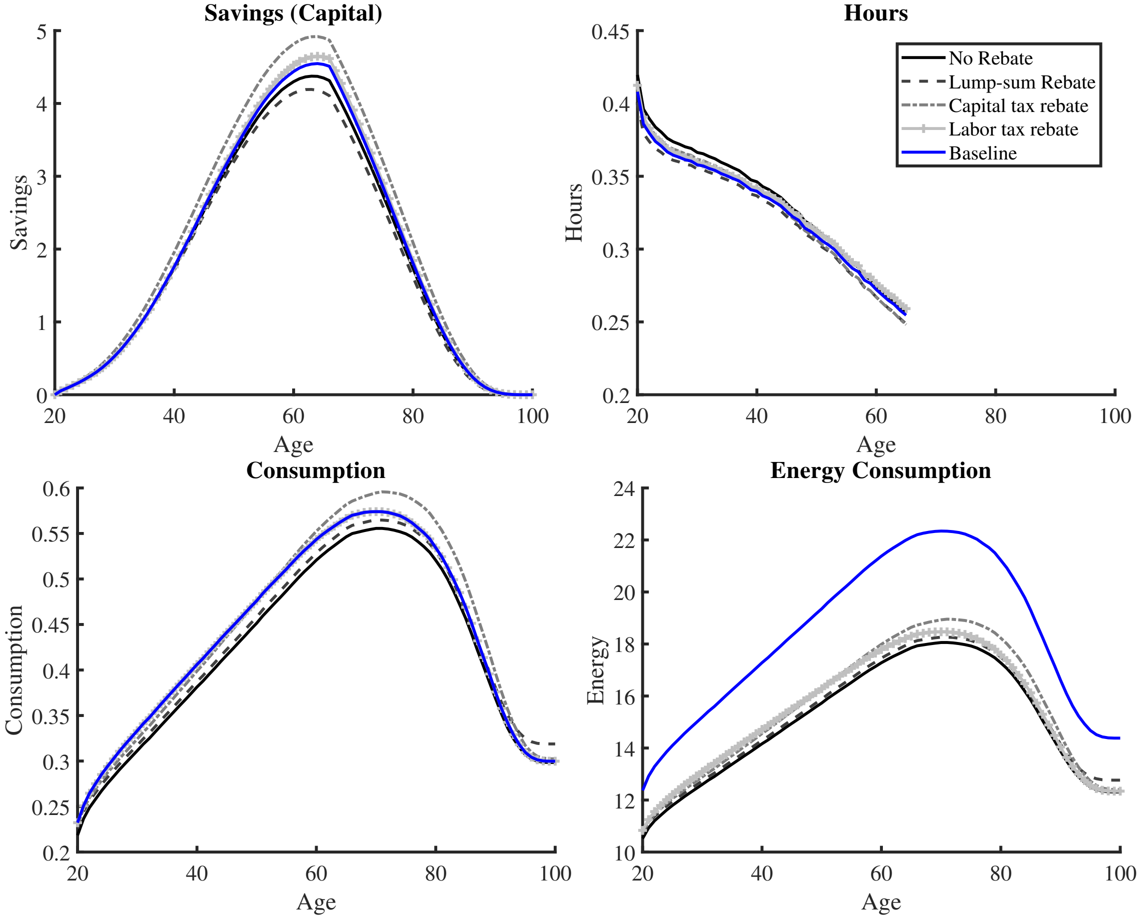
[36] Figure 8 in the Appendix displays the change in hours worked over the life cycle in the steady state. Note that under the capital tax rebate policy, the efficiency hours (N) falls slightly due largely to the fact that agents shift hours to the less productive early years of their working lifetimes.

[37] Not only are retired agents receiving a lump-sum transfer from the carbon tax revenue, their Social Security benefits also increase in response to the carbon tax, ensuring that the purchasing power of the Social Security benefits is not eroded.

the higher after-tax risk-free rate under the capital-tax rebate encourages agents to delay consumption until later in life since an additional unit of consumption for a young agent costs more in terms of forgone future consumption (bottom left panel of Figure 8). Agents also shift hours to earlier in life because the increase in the after-tax risk-free rate raises the the return to working more for younger agents than for older agents (top right panel of Figure 8). Analogous reasoning reveals that the fall in the risk-free rate under the labor-tax rebate causes agents to shift consumption to earlier in life and hours to later in life.

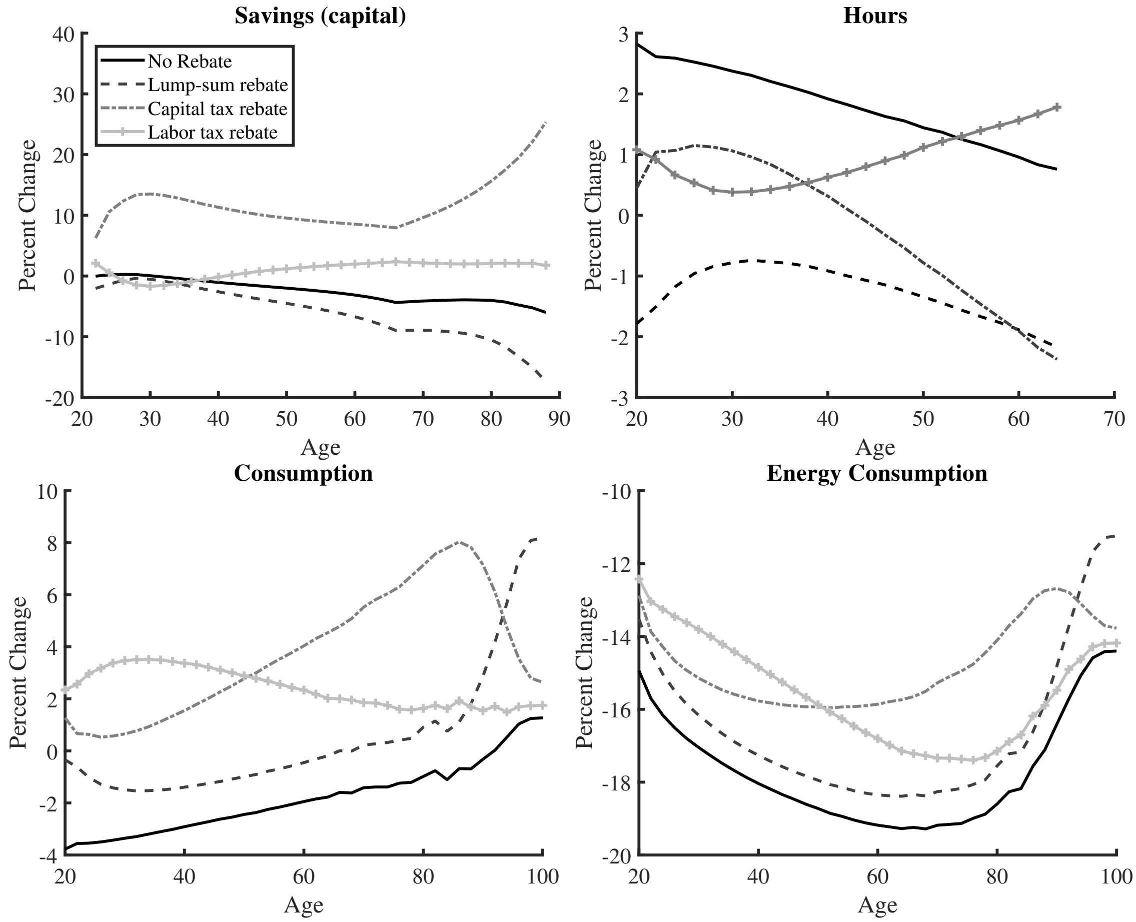
Finally, in all four simulations, energy use is lower in every period of the life cycle because the carbon tax raises the relative price of energy (bottom right panel of Figure 8). This change in energy consumption is generally largest for the middle-aged agents. The level of energy consumption is highest for this age group, implying that their energy demand is the most elastic.

Figure 7: Lifecycle Profiles: Levels



Note: For each tax policy, the figure plots the average level of savings, hours, consumption, and energy consumption for each age cohort. The profiles are in the steady state.

Figure 8: Lifecycle Profiles: Percent Change From Baseline



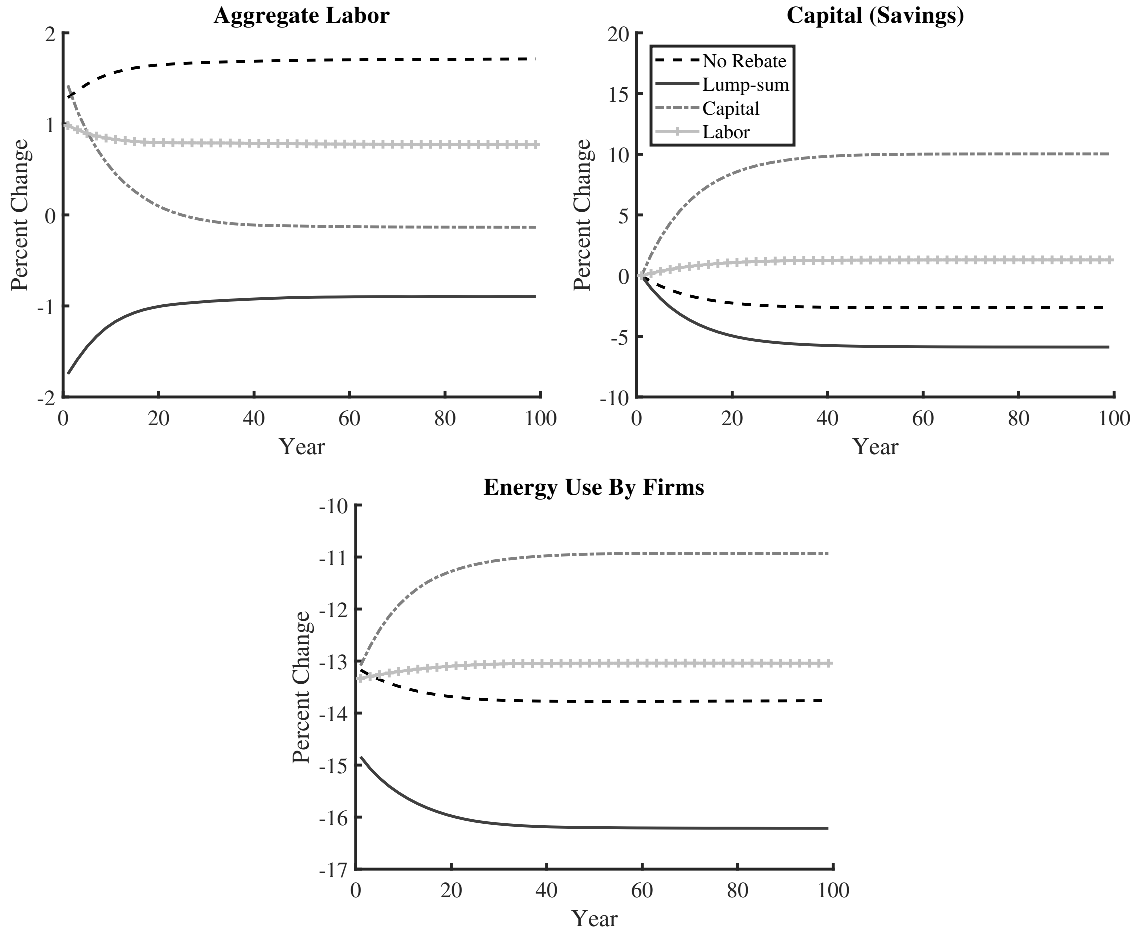
Note: The figure plots the percent change under the carbon tax policy from the baseline case in the average savings, hours, consumption and energy consumption for each age cohort. The profiles are in the steady state.

C.2 Transition

The results presented in Figure 2 in Section 4.2 reveal that, in response to the adoption of a carbon tax policy, factor prices can experience very different changes in the short-term versus the long-run. These different responses are driven by changes in firms' demand for different inputs as the economy transitions to the new long-run equilibrium with the policy in place. This is particularly true under the capital tax rebate policy and the lump-sum rebate policy. Under the capital tax rebate policy, the steady-state after-tax risk-free rate increases by only 8.78 percent (see Table 9). However, immediately after the tax policy is adopted, the after-tax risk-free rate increases by over 30 percent before steadily falling to its new long-run level. Figure (9) highlights why this pattern emerges. When the capital tax rebate policy is implemented, capital does not instantly adjust to the new long-run level, but rather, steadily increases towards the long-run steady state level as agents invest in more savings. In contrast, right after the policy is implemented, agents discontinuously increase their hours worked in order to begin accumulating savings. The large jump in the hours worked causes a substantial decline in the wage and increases the after-tax risk-free rate well beyond the future long-run steady state level.

Similarly, the near-term factor price changes induced by the lump-sum rebate policy differ meaningfully from the long-run factor price changes. In the long-run, the after-tax risk-free rate increases by 4.57 percent and the after-tax wage falls by 4.19 percent. However, immediately after the lump-sum rebate policy is adopted, the after-tax risk-free rate falls by over 5 percent and the after-tax wage falls by less than 2 percent (see Figure 9). Again, the differences in the near-term and long-run factor price changes are largely explained by the slow updating to the capital stock. While capital ultimately falls by 5.88 percent in the steady state, the drop in the capital stock occurs slowly over the transition. In contrast, immediately after the policy is adopted, aggregate labor discontinuously falls as agents reduce their demand for savings. This reduction in labor drives the after-tax risk-free rate down more in the near-term and dampens the near-term reduction in the after-tax wage.

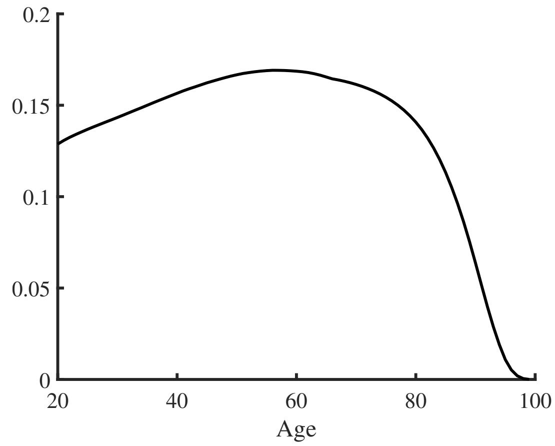
Figure 9: Transition Dynamics: Percent Change From the Baseline



Note: The figures plot the percentage changes in the after-tax returns to capital and labor, as well as the aggregate labor, capital, and energy use by firms, relative to the baseline steady state values during the years after the policy is adopted. Year zero is the first year under the policy.

Finally, the discussion in Section 4 reported the magnitude of the distributional effects for the living population by calculating the percent change in the Gini coefficient relative to its value in the baseline with no carbon tax. To calculate the Gini coefficient among the living population, we first calculate the Gini coefficient for each age cohort from the expected remaining lifetime welfare for agents in that cohort. For reference, Figure 10 plots the Gini coefficient for each age cohort in the baseline. The Gini coefficient is humped shaped over the life cycle, rising until agents near retirement and then falling. The initial inequality among the 20 year old age cohort is driven by the distribution in the initial productivity shocks each agent receives at birth. As agents age and receive additional productivity shocks, inequality continues to grow over the agents' working lifetimes. For cohorts that are retired, the progressive Social Security system steadily reduces this inequality. The aggregate Gini coefficient for the living population is a weighted average of the Gini coefficient in each age cohort.

Figure 10: Gini Coefficient for Each Age-Cohort: Baseline



Note: Figure shows the Gini coefficient for each age cohort in the baseline. We calculate the Gini coefficient for a given age cohort from each household's remaining lifetime welfare. For example, for households who are 25, we calculate the Gini coefficient from the expected remaining lifetime welfare starting at age 25.

D Robustness

D.1 Endogenous Energy Production

In the preceding analysis, we assumed that energy could be purchased from a world market at a constant price. Under this assumption, the energy price does not endogenously respond to the adoption of a domestic carbon tax. In reality, if the U.S. were to adopt a carbon tax, total demand for fossil energy would decline, and the domestic and world energy prices would decrease. Ultimately, the decline in the energy price would likely be small.Nonetheless, we alter our modeling assumptions in order to examine whether the key findings from the preceding analysis are driven by the imposition of an exogenous world energy price.

To allow the energy price to endogenously respond to the adoption of a carbon tax, we analyze a two-sector model in which both the final good and energy are only produced domestically. Assuming that all energy is produced and sold domestically will dramatically overstate the endogenous decline in the energy price caused by the adoption of a carbon tax. Therefore, we view our previous model as our preferred specification.

In the endogenous energy price case, firms produce energy from capital and labor. As in the main specification, this energy is used as an input to the production of the final good and is also consumed directly by the household. Following Barrage (2016), both the energy and final good sectors are perfectly competitive with Cobb-Douglas production technologies

$$Y_t = A_{1,t} K_{1,t}^{\alpha_1} N_{1,t}^{1-\alpha_1-\psi} (E_t^p)^{\psi} \quad \text{and} \quad E_t = A_{2,t} K_{2,t}^{\alpha_2} N_{2,t}^{1-\alpha_2}, \tag{19}$$

where subscript "1" denotes inputs used in the final good sector and subscript "2" denotes inputs used in the energy sector. Market clearing requires $K_{1,t} + K_{2,t} = K_t$, $N_{1,t} + N_{2,t} = N_t$, and $E_t^p + E_t^c = E_t$. The remainder of the model is the same as in the main specification.

This production structure introduces three new parameters to calibrate: the energy share in the production of final good, ψ, capital share in the production of the final good, α_1, and capital share in the production of energy α_2. We use 0.04 for the energy share in the production of the final good.[38] Following Barrage (2016), we set capital share in the production of the final good equal to 0.3 and capital share in the production of energy equal to 0.597. We recalibrate the remaining parameters to match the same targets in Table 2.

To examine the non-environmental welfare impacts of the alternative carbon tax policies, we again calculate the CEV for an agent born into the future steady state and the CEV for each cohort alive at the time the policy is adopted. Table 10 reports the average CEV under each policy in the steady state as well as among the living agents. Just as we found in the exogenous energy price case (see Table 3), the non-environmental welfare costs imposed on the agents alive when the policy is adopted differ meaningfully from the long-run welfare costs. Again, the capital and labor tax rebate policies impose larger costs among the cohorts

[38]This is similar to the value of 0.03 used by Barrage (2016) and Golosov et al. (2014).

alive at the time the policy is adopted while the non-environmental welfare cost of the uniform lump-sum rebate policy is larger in the future steady state.

Table 10: Aggregate Welfare Effects With Endogenous Energy Production (CEV, percent)

	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Steady State	-5.33	-1.04	-0.04	-0.58
Living Population	-3.95	0.11	-0.14	-0.75

Tables 11 and 12 summarize the CEV across income quintiles under each policy in the new steady state and among the living population. Again, allowing the energy price to endogenously respond to the adoption of the carbon tax does not qualitatively change the results. During the transition and in the long-run, the uniform lump-sum rebate policy is progressive while the capital and labor tax rebate policies are regressive. Moreover, the regressivity of the capital tax rebate is more extreme among the living agents while the regressivity of the labor tax rebate policy is more extreme in the long-run steady state.

Table 11: Steady State Welfare Effects With Endogenous Energy Production: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV By Quintile (percent)				
Quintile 1	-5.50	0.26	-0.34	-1.33
Quintile 2	-5.36	-0.72	-0.13	-0.80
Quintile 3	-5.27	-1.32	0.04	-0.45
Quintile 4	-5.20	-1.91	0.21	-0.06
Quintile 5	-5.21	-2.55	0.24	0.41
% $\Delta\mathcal{G}$ From Baseline Value of 0.13				
	0.81	-3.34	0.91	2.03

Table 12: Welfare Effects For the Living Population With Endogenous Energy Production: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV (percent)				
Quintile 1	-3.97	1.63	-0.79	-1.13
Quintile 2	-3.93	0.42	-0.33	-0.82
Quintile 3	-3.92	-0.26	0.02	-0.65
Quintile 4	-3.93	-0.93	0.38	-0.49
Quintile 5	-3.97	-1.69	0.68	-0.32
% $\Delta\mathcal{G}$ From Baseline Value of 0.15				
	0.16	-3.62	1.76	0.81

D.2 Subsistence Energy Consumption

To ensure that our model captured the observed negative relationship between income and expenditure shares, we specified we assumed that all agents must consume a minimum amount of energy, $\bar{e}$, and that the agents receive no utility from this subsistence level of energy consumption. To provide insight into how the non-homotheticity affects the results presented in Section 4, we analyze the special case when $\bar{e} = 0$ and, thus, the energy expenditure share is constant across income groups. The remainder of the model is the same as in the baseline specification. We recalibrate the parameters to match the same targets in Table 2 under the modification that $\bar{e} = 0$.

Table 13 presents the aggregate CEV under each policy in both the future steady state and among the living population assuming the utility function is now homothetic. Compared to the earlier results from the case where $\bar{e} > 0$ (see Table 3), the results are effectively unchanged. Again, the lump-sum rebate policy is less costly among the living population while the capital and labor tax rebate policies impose higher non-environmental welfare costs on the living population.

Table 13: Aggregate Welfare Effects with $\bar{e} = 0$ (CEV, percent)

	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Steady State	-6.35	-1.30	0.30	-0.35
Transition	-4.65	0.11	-0.03	-0.69

While assuming homotheticity does not meaningfully alter the average welfare impacts of the carbon tax policies simulated, it does alter how the non-environmental welfare costs are predicted to be distributed across income groups. To highlight how the distributional impacts are affected by the homotheticity assumption, Tables 14 and 15 summarize the CEV across income quintiles in the new steady state and among the living population. Compared to the earlier results from the case where $\bar{e} > 0$ (see Tables 5 and 6), each policy is now less regressive (or more progressive). For example, assuming $\bar{e} = 0$, we find that under the no-rebate case, the Gini coefficient falls by 0.26 percent in the steady state and 0.49 percent among the living population. Effectively, given that the energy expenditure share is no longer larger among the lower income groups, the direct effect of the carbon tax is no longer regressive. Regardless of the value of $\bar{e}$, however, the same pattern emerges. The capital tax rebate policy is more regressive among the living population while the labor tax rebate policy is less regressive among the living agents.

Table 14: Steady State Welfare Effects With $\bar{e} = 0$: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV By Quintile (percent)				
Quintile 1	-6.10	0.76	0.36	-0.90
Quintile 2	-6.28	-0.79	0.29	-0.53
Quintile 3	-6.38	-1.74	0.33	-0.27
Quintile 4	-6.49	-2.65	0.29	0.03
Quintile 5	-6.71	-3.66	0.13	0.41
% $\Delta\mathcal{G}$ From Baseline Value of 0.13				
	-0.26	-5.25	-0.02	1.47

Table 15: Welfare Effects for the Living Population With $\bar{e} = 0$: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV (percent)				
Quintile 1	-4.37	2.28	-0.56	-0.90
Quintile 2	-4.59	0.53	-0.21	-0.73
Quintile 3	-4.72	-0.44	0.13	-0.64
Quintile 4	-4.83	-1.35	0.41	-0.54
Quintile 5	-4.97	-2.39	0.73	-0.48
% $\Delta\mathcal{G}$ From Baseline Value of 0.15				
	-0.49	-4.91	1.54	0.38