

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

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January 30, 2017

Abstract

This paper examines the non-environmental welfare effects of introducing a revenue-neutral carbon tax policy. Using a life cycle model, we find that the welfare effects of the policy differ substantially for agents who are alive when the policy is enacted compared to those who are born into the new steady state with the carbon tax in place. Consistent with previous studies, we demonstrate that, for those born in the new steady state, the welfare costs are always lower when the carbon tax revenue is used to reduce an existing distortionary tax as opposed to being returned in the form of lump-sum payments. In contrast, during the transition, we find that rebating the revenue with a lump-sum transfer is less costly than using the revenue to reduce the distortionary labor or capital tax. Additionally, we find that, depending on how the carbon tax revenue is rebated, the policy can be substantially more regressive over the transition than in the steady state. Overall, our results demonstrate that estimates of the non-environmental welfare costs of carbon tax policies that are based solely on the long-run, steady state outcomes may ultimately paint too rosy of a picture. Thus, when designing climate policies, policymakers must pay careful attention to not only the long-run outcomes, but also to the transitional welfare costs and regressivity of the policy.

Keywords: Carbon taxation; overlapping generations

JEL codes: E62; H21; H23

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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)). These policies clearly have the potential to provide large welfare gains through environmental channels – e.g., reducing the risks posed by climate change and improving air quality. However, they can also significantly affect welfare through non-environmental channels. Specifically, by increasing the relative price of energy derived from fossil fuels, a carbon tax can alter individuals’ decisions to consume, work, and save – potentially causing large general equilibrium impacts across the entire economy.

Previous studies highlight that the way in which revenue from a carbon tax is used can dramatically alter the non-environmental welfare consequences of a tax policy. In particular, using carbon tax revenue to reduce pre-existing distortionary taxes (e.g., taxes on labor or capital income) has been shown to be far more efficient than recycling the revenue in the form of lump-sum rebates – a result referred to in the literature as the ‘weak double-dividend hypothesis’ (Goulder (1995), de Mooij and Bovenberg (1998), Bovenberg (1999)). Previous studies also highlight that the revenue recycling method can substantially alter the distribution of the welfare changes across income groups (Fullerton and Heutel (2007), Dinan and Rogers (2002), Metcalf (2007), Parry (2004), Parry and Williams (2010)).

While these previous studies provide a solid understanding of the long-run welfare and distributional impacts of revenue-neutral carbon tax policies, they may provide little insight into how the current, living population will be impacted. Specifically, much of the existing work examines the welfare effects by comparing steady state outcomes in an economy with and without a carbon tax. This comparison ignores how these welfare effects may differ during the transition between the two steady states. Differences across the near-term and welfare effects can arise for two main reasons. First, following the adoption of a carbon tax policy, the returns to capital and labor may not immediately adjust to their new, long-run steady state levels. Second, while agents born into the new steady state experience the

carbon tax policy for their entire life cycle, those alive at the time carbon tax is adopted only experience the new policy for a portion of their life cycle. Consequently, if the welfare costs of the new policy vary over the life cycle, the average welfare costs may differ in the transition versus in the long-run steady state.

In this paper, we examine how the non-environmental welfare impacts of revenue-neutral carbon tax policies differ in the long-run steady state versus during the transition to the new steady state. To do so, we follow the dynamic public finance literature (e.g. Conesa et al. (2009); Conesa and Krueger (2006); Peterman (2013)) 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 CO₂. 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. Exploring the impacts of these carbon tax policies in a life cycle model with income heterogeneity turns out to be particularly important because, as our results demonstrate, the welfare effects differ substantially by income and age.

Using our life cycle model, we first solve for the impact each carbon tax policy will have on the expected lifetime welfare of an agent born in the new, long-run steady state. We then compare the steady state welfare changes to the impacts each policy will have on the expected welfare of agents alive at the time the policy is introduced. Focusing first on the steady state effects, our results echo the findings from the existing literature. In the steady state, the expected non-environmental welfare costs are lower when the carbon tax revenue is used to reduce either existing distortionary tax. In fact, our results suggest that using the carbon tax revenue to offset revenue generated by the capital tax actually reduces the distortions caused by the tax system – leading to an increase in the expected non-environmental welfare equivalent to 0.29 percent of expected lifetime consumption. In contrast, recycling the revenue in the form of uniform lump-sum payments results in a decrease in non-environmental welfare equivalent to 1.26 percent of an agent’s expected lifetime consumption. The distributional

impacts in the steady state also reiterate the findings from the earlier literature. If carbon tax revenue is recycled through uniform lump-sum payments, low income households are the relative winners. Alternatively, if the revenue is used to reduce a pre-existing distortionary tax, then the higher income households are the relative winners.

While understanding how alternative policies can impact agents' welfare in the long-run is important, our results reveal that the steady state impacts serve as poor predictions of how the current, living population will be affected. In particular, we find that using carbon tax revenue to reduce the labor or capital tax will be more costly during the transition. Focusing specifically on the cohorts 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 the policy is adopted will experience an average welfare increase of only 0.06 percent of expected future lifetime consumption – approximately one fifth as large as the expected welfare increase experienced by agents born into the future steady state. In contrast, the lump-sum rebate policy, which causes a sizable reduction in the expected welfare of an agent born in the future steady state, actually leads to an increase in average welfare among the living population equal to 0.26 percent of expected future lifetime consumption. That is, of the policies we examine, the lump-sum rebate results in the largest reduction in steady state welfare but also causes the largest increase in welfare among the living population.

The welfare impacts a given policy has on living agents can differ meaningfully from the expected welfare impact on an agent born into the future steady state for two reasons. First, unlike agents born into the steady state, agents alive when the carbon tax is adopted only experience the carbon tax 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 can vary substantially with the agent's age. For example, when agents are young, the lump-sum rebate policy is detrimental primarily due to a decline in the wage. In contrast, retired

agents benefit from the lump-sum rebates of the carbon tax revenue but are unharmed by the decline in the wage.¹ For an agent born into the steady state under the lump-sum rebate policy, the welfare costs incurred early in the life cycle outweigh the welfare gains later in the life cycle. As a result, expected lifetime welfare falls in the steady state. However, among the agents alive when the lump-sum rebate policy is adopted, a large share of the population has already lived beyond the period when the lump-sum rebate policy is relatively more costly. Consequently, among the living agents, the lump-sum rebate policy leads to an increase in the average non-environmental welfare.

The second reason why a carbon tax policy can affect living agents differently than agents born into the future steady state is that the near-term and long-run factor price responses can differ substantially. For example, under the capital tax rebate policy, the after-tax returns to capital and the wage both increase in the long-run steady state. Because the capital stock slowly adjusts, immediately after the capital tax rebate policy is adopted, the after-tax returns to capital experience a substantial increase – approximately 3.5 times larger than the ultimate long-run increase – while the after-tax wage falls. The larger immediate increase in the return to capital benefits wealthy living agents – and particularly those around the age of retirement who have accrued the highest levels of capital. However, the immediate decline in the after-tax wage makes younger living agents worse off than agents born into the future steady state. As a result, compared to the long-run welfare effects, the capital tax rebate policy provides a much smaller increase in the average welfare of living agents and is much more regressive.

The present paper builds on several related 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. It is important to stress that, in contrast to Leach’s analysis, we focus exclusively on the non-environmental welfare impacts of carbon tax policies. However, across each of the policy options we simulate, the reduction in energy consumption is very

¹In addition, the retirees are insulated from the direct costs of the carbon tax because Social Security payments adjust to changes in the cost of living caused by the tax.

stable. As a result, the welfare changes driven by environmental quality improvements will be similar across the policies we consider. 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.²

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.³ The inclusion of within cohort heterogeneity enables us to directly examine the general equilibrium welfare impacts not only across age groups, but also across income groups.⁴ In addition, by modeling households' utility using a non-homothetic 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 objective is to illustrate an important point: the welfare and distributional impacts of revenue-neutral carbon tax policies can differ dramatically across agents alive during the transition and those born into the future long-run steady state.⁵ This suggests that when designing and evaluating alternative carbon tax policies, it is crucial to consider how welfare will be affected not only in the long-run steady state, but also during the transition to the new steady state. In particular, when evaluating policies that use carbon tax revenue to reduce preexisting distortionary taxes, our results reveal that estimates of the non-environmental welfare costs

²Rausch (2013) also consider the impacts of using carbon tax revenues to reduce the size of the federal debt.

³Chiroleu-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 a carbon tax in the steady state – not over the transition for an agent already in the model when the tax is adopted. In addition, the authors focus solely on recycling carbon tax revenues through a labor tax rebate.

⁴To predict the distributional impacts, Williams et al. (2015) instead use the estimates from Carbone et al. as inputs in a partial equilibrium, microsimulation model that 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.

⁵Previous 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)).

based solely on the long-run steady state outcomes may ultimately paint too rosy a picture.

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 reports the steady state and transition results under the alternative, revenue-neutral carbon tax policies. Section 5 examines the robustness of the results under alternative modeling assumptions, and Section 6 concludes.

2 Model

The following section describes the OLG model we use to examine the welfare and distributional impacts of various revenue-neutral carbon tax policies.

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 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. At age j , agent i earns labor income $y_{i,j,t}^h \equiv w_t \cdot \mu_{i,j,t} \cdot h_{i,j,t}$, 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. The log of an agent's idiosyncratic productivity consists of four additively separable components,

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

This specification is based on the estimates in Kaplan (2012) from the Panel Study of Income Dynamics (PSID). 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:

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

Thus, agents across cohorts are differentiated on average along one dimension that affects their labor productivity: 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 permanent 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 a 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, $e_{i,j,t}^c$.

As previous studies highlight (e.g., Metcalf (2007), Hassett et al. (2009)), the direct impact of a carbon tax – prior to any revenue recycling – is likely to be quite regressive. This is driven by the fact that lower income households devote a larger share of their consumption 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.

In each period t , agent i 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

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

We take the expectation in equation (3) with respect to the stochastic processes governing the idiosyncratic productivity shocks. Agents incorporate mortality risk by discounting the next period's utility by Ψ_j . In addition, they discount future utility by β , the discount factor. An agent's utility increases with consumption of either energy or the generic consumption good and decreases with more hours worked. Note, we do not account for the environmental impact from reductions in total energy use in the utility function. Instead, our focus is solely on the non-environmental effects of the carbon tax policy.

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.⁶

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 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.

⁶In 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/>.

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 his assets plus the return on any assets he 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 his labor income, $y_{i,j,t}^h$, net of his 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 lead to lower carbon emissions. The carbon tax, τ^c , places 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 $p^e + \tau^c$.⁷ In one of the tax policies, the government rebates this carbon-tax revenue through uniform lump-sum transfers to the households, T_t^c .

⁷Given 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.

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. In addition, we signify an agent's level of capital savings in the subsequent period as a' . The individual state variables, x , are asset holdings, a , idiosyncratic labor productivity, μ , and age j . 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 $U : \mathbb{R}_+ \times \mathbb{R}_+ \times \mathbb{R}_+ \rightarrow \mathbb{R}_+$ and factor prices, $\{w, r, p^e\}$, 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:

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

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

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

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

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

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

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

3. The Social Security tax satisfies:

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

4. Transfers from accidental bequests satisfy:

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

5. The government budget balances:

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

6. Markets clear:

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

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

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 an age of 20. Agents are exogenously forced to retire at age $j^r = 66$. If an individual survives until age 100, he 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 idiosyncratic labor productivity shocks based on the estimates from the PSID data in Kaplan (2012).⁸ These parameters governing the permanent, persistent, and transitory idiosyncratic shocks to individuals' productivity are set such that the shocks are distributed 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 $\sigma_{\theta}^2 = 0.081$.⁹ We discretize all three of the shocks in order to solve the model, using two states to represent the transitory and permanent shocks

⁸For details on estimation of this process, see Appendix E in Kaplan (2012).

⁹These are the parameter values on the log of the productivity processes.

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	$\frac{G}{Y} = 0.155$

and five states for the persistent shock.¹⁰ 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

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

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 0.5.¹¹

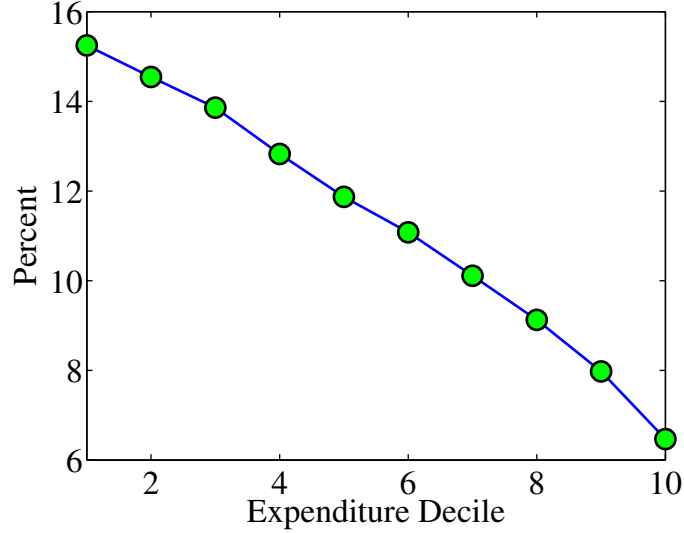
Recall, previous studies demonstrate that the carbon tax by itself will be regressive because lower income individuals devote a larger share of their total consumption expenditures to energy.¹² Figure 1 plots the average energy budget share for each expenditure decile using data from the Consumer Expenditures 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.

¹⁰We 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)).

¹¹Peterman (2016) demonstrates that setting the Frisch elasticity at 0.5 is consistent with including hours fluctuations on the intensive margin only.

¹²See Metcalf (2007) and Hassett et al. (2009).

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 used 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

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

If $\bar{e} = 0$, energy share equals $1 - \gamma$ regardless of the level of an agent’s total expenditures. However, if $\bar{e} > 0$, energy share will decrease with expenditures. Moreover, higher \bar{e} increases the responsiveness of energy share to changes in total expenditures. 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.¹³

Table 2 reports the value of the moments we target in the model and their corresponding value in the data.¹⁴ Overall, the model fits these consumption data quite closely. For example, the first line of Table 2 reports that energy share in the data is 0.102 and energy share in the model is 0.100.

Table 2: Model Fit

Moment	Data	Model
Energy share: Ω	0.102	0.102
Energy share difference: $\Delta\Omega$	-0.128	-0.128
Hours: H	0.333	0.274
Govt spending to output: $\frac{G}{Y}$	0.155	0.155
Capital to output: $\frac{K}{Y}$	2.7	2.70

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,

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

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.

¹³The 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 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 $\frac{54}{142} = \frac{-12.8}{-33}$.

¹⁴Note that in the data column, we report the percent difference in energy share ($\Delta\Omega$) adjusted for the smaller expenditure variance, since this is the value we target.

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 (e.g., Castaneda et al. (2003), Conesa and Krueger (2006), Conesa et al. (2009), Peterman (2013)) and use estimates of the U.S. tax code from Gouveia and Strauss (1994). Gouveia and Strauss (1994) match the U.S. income tax code to the data using a three parameter functional form,

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

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.¹⁵

We determine government consumption, G , so that it equals 15.5 percent of output, its average empirical value in the U.S data.¹⁶ We set the tax rate on capital income, τ^k , to

¹⁵U.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 of Social Security income is taxable for single households with total income above 25,000 in 2014 dollars. We translate these level thresholds to thresholds based on the percentage of labor income using data on estimated average earnings in the Annual Statistical 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 description of U.S. tax law as it applies to Social Security benefits.

¹⁶To 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.

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 fifty percent of the average income of all working individuals

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

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 he could in the baseline steady state.¹⁷ 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 CO₂. This value is in line with the central estimate of the social cost of carbon used in cost-benefit analyses performed by the U.S. Government.¹⁸ 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

¹⁷Specifically, Social Security payments in each simulation equal Social Security payments in the baseline times the ratio $\frac{c^e(p^e + \tau^c)}{c^e p^e + c}$ where c^e and c are the baseline values of energy and non-energy consumption, respectively.

¹⁸In particular, the IAWG (2013) reports a central carbon cost estimate of \$38/ton of CO₂ in 2015 dollars.

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 CO₂.¹⁹ We simulate three different policies which vary in how the government rebates the revenue generated from the carbon tax: (1) rebates through 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 in which the government does not rebate the carbon tax revenue and instead uses it in a non-productive sector (i.e. “throws it into the ocean”). We refer to this case as the no-rebate policy.

Under the different policies, 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.²⁰ Tables 3 and 4 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 ,

¹⁹To solve for the competitive equilibrium in the baseline and under each tax policy, we use a modified algorithm based on Heer and Maussner (2009). For details on the steady state and transition solution algorithms, see Appendix B.

²⁰In 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.

because the government throws the carbon-tax revenue into the ocean.

Table 3: 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 4: 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	-	-

We focus on understanding the welfare consequences of the different policy options. Consistent with much of the double-dividend literature, we specifically examine the non-environmental welfare consequences of the carbon tax policies. Ultimately, the subsequent results reveal that the reduction in energy use, and as a result, the welfare changes caused by improvements in environmental quality, are likely to be similar across the different rebate options. In Section 4.2, we begin by analyzing the welfare consequences of the policies for agents born in the future long-run steady state. In Section 4.3, we then explore how the welfare effects differ for agents alive at the time the carbon tax is implemented.²¹

²¹The welfare implications for agents who are born during the transition are reported in the Appendix.

4.2 Steady State Welfare Effects

4.2.1 Aggregate welfare effects in the steady state

To compare the steady state welfare impacts across the different policy options, we calculate the consumption equivalent variation (CEV) for each of the four counterfactual economies. The CEV measures the uniform percentage change in an agent’s expected consumption that is required to make them indifferent – prior to observing their idiosyncratic ability, productivity, and mortality shocks – between the old baseline steady state and the steady state under the new carbon tax policy. Thus, a negative value for the CEV indicates that the agent’s expected non-environmental welfare is reduced by the carbon tax policy. A positive CEV indicates that the expected non-environmental welfare increases under the carbon tax policy.

The first row of Table 5 reports the aggregate CEVs in the steady state under the four carbon tax policies. Consistent with the literature on the weak double dividend hypothesis (Goulder (1995), de Mooij and Bovenberg (1998), Bovenberg (1999)), the non-environmental welfare costs of a carbon tax policy are lower when the government uses the carbon tax revenue to offset a pre-existing distortionary tax. 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. The positive CEV under the capital tax rebate suggests that this policy reduces the overall distortions in the tax system, and, as a result, expected non-environmental welfare increases in the steady state.

Table 5: Aggregate Welfare Effects (CEV, percent)

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

To further understand the responses to the various tax policies, Table 6 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.²² 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.

Table 6: Steady State Aggregates

	Baseline	Percent Change From Baseline: Carbon Tax			
		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' incentives to save. In addition, the price change also distorts the household's intratemporal

²²We define the net (after-tax) efficiency wage as $(1 - \bar{\tau}^l)w$ where $\bar{\tau}^l$ is the average labor-tax rate.

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 6 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.²³ 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.²⁴ 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.

²³Figure 9 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.

²⁴Not 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.

4.2.2 Distribution of welfare effects in the steady state

The preceding results summarize how the various carbon tax policies would, *on average*, affect the non-environmental welfare of an agent born into the future steady state. Under any of the policies, however, the welfare effects are far from uniform. While some agents will benefit from a given policy, others will be made worse off. The first row of Table 7 reports the probability that a given carbon tax policy will increase a steady state agent’s lifetime non-environmental welfare relative to the baseline. While the capital tax rebate increases aggregate welfare in the steady state, these welfare gains are only experienced by 74 percent of the population. Likewise, even though the labor tax and lump-sum rebates reduce aggregate welfare in the steady state, 43 percent and 13 percent of the population, respectively, experience non-environmental welfare gains.

Table 7: Probability of a Welfare Gain (percent)

	No Rebate	Lump-sum Rebate	Capital Rebate	Labor Rebate
Steady State	0	13	74	43
Transition	0	53	59	13

Much of the heterogeneity in the welfare effects stems from differences in how the policies impact individuals across the income distribution. To analyze the distributional impacts, we 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 8 shows the CEV by income quintile for each tax policy. 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 8: Steady State Welfare Effects: Distribution

	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV By Quintile (percent)				
Quintile 1	-6.62	0.47	0.03	-1.21
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	-4.38	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 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

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

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 (i.e. it decreases inequality).

Referring to the bottom row of Table 8, the no rebate case demonstrates that the carbon-tax by itself is slightly more costly for lower income agents, resulting in an increase in the Gini coefficient of 0.84 percent.²⁵ In large part, the carbon tax by itself is regressive because lower

²⁵The 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.

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.²⁶

The way in which the government rebates carbon tax revenue can either exacerbate or mitigate the regressivity of the carbon tax policy. Under the lump-sum rebate policy, each agent receives an equal transfer. As a result, agents with lower lifetime incomes receive a larger percentage increase in their total lifetime income. Consequently, the policy leads to a reduction in the Gini coefficient of 4.38 percent. Thus, 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 carbon tax revenues by reducing the capital tax causes the Gini coefficient to rise by 0.86 percent. The left panel of Figure 2 highlights that agents with higher lifetime income receive a larger share of their total income from capital.²⁷ As a result, these higher income agents receive a larger direct benefit from the reduction in the capital tax, causing the rebate to be regressive. It is important to note, however, that the increase in regressivity under the capital tax rebate is similar to the no-rebate case. The capital tax rebate leads to an increase in the size of the economy and to increases in accidental bequests (Table 6), both of which have positive wealth effects across all of the income quintiles. The concavity of the utility function implies that the welfare gains from these wealth effects are larger for the lower income quintiles, mitigating almost all of the regressive effects from the capital tax rebate.

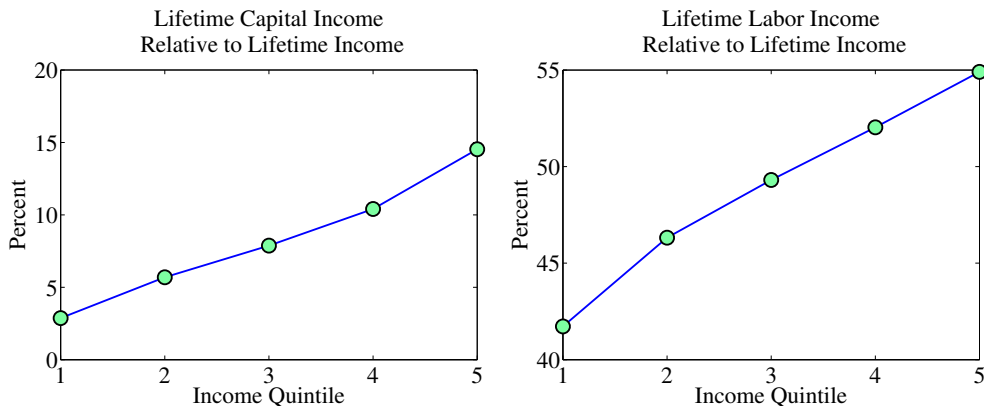
The regressivity of the labor tax rebate policy is even more pronounced; the Gini coefficient increases by 2.36 percent under the labor tax rebate as opposed to the 0.86 percent increase under the capital tax rebate. Again, the right panel of Figure 2 highlights that agents with high lifetime income receive a larger share of their total income from labor. As

²⁶It 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 $\bar{e} = 0$.

²⁷Note, 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.

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.

Figure 2: Capital and Labor Income as a Fraction of Total Lifetime Income



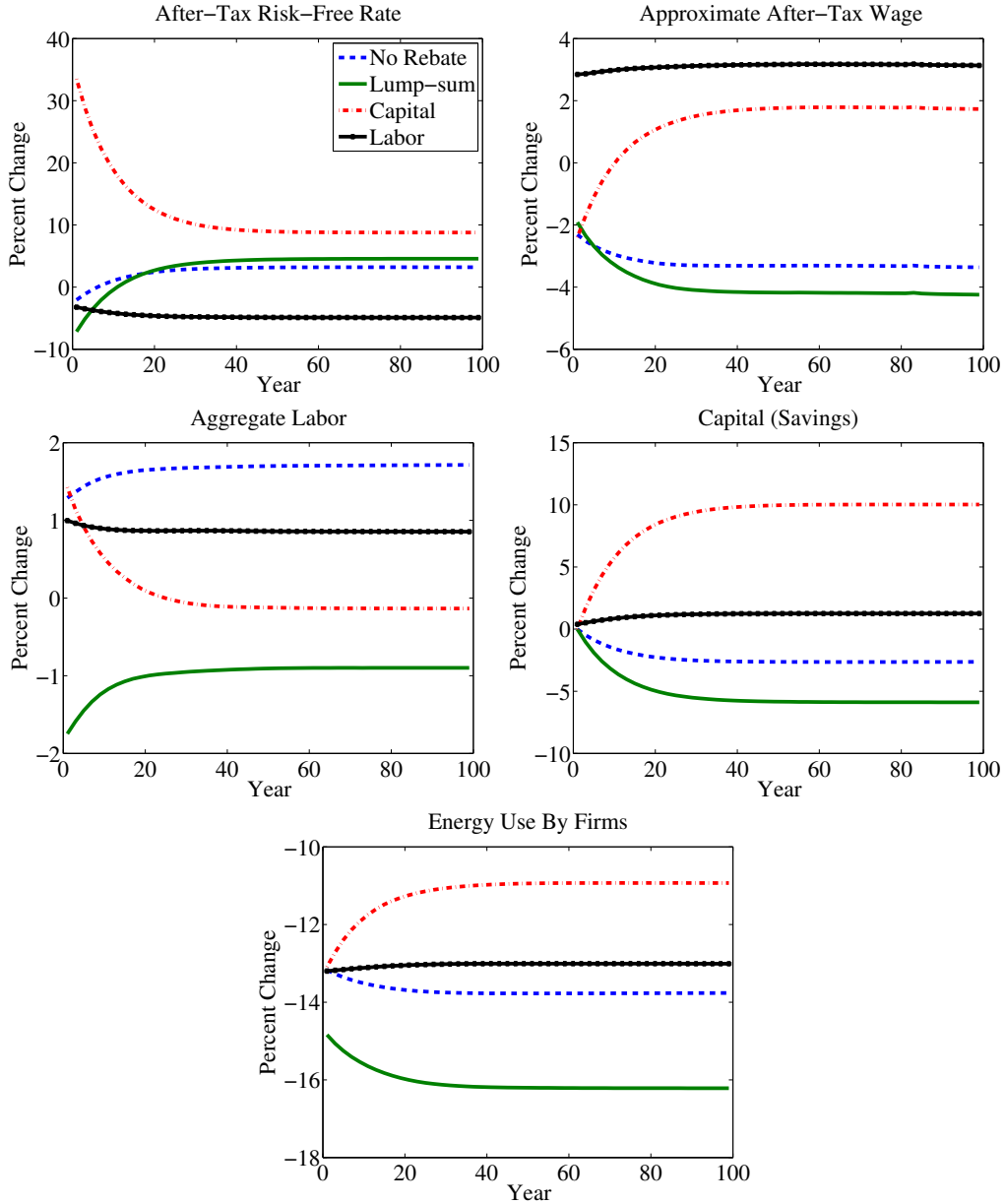
Note: The left panel displays the share of lifetime income accounted for by capital income under the carbon tax policy that uses carbon revenues to reduce capital taxes. The right panel displays the share of lifetime income account for by labor income under the carbon tax policy that uses carbon revenues 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.

4.3 Transition

4.3.1 Transition: Aggregate Welfare Effects

The preceding results reveal that, in the future steady state, different revenue-neutral carbon tax policies will have very different non-environmental welfare effects. Moreover, the results highlight that much of the variation in the steady state welfare effects can be explained by the resulting long-run changes in the factor prices due to the changes in taxes and the levels of capital and aggregate labor. For example, under the capital tax rebate policy, the steady state after-tax returns to capital increase. This causes capital to increase substantially which leads to growth in wages, production, and ultimately consumption. In contrast, under the costly lump-sum rebate policy, agents reduce capital savings leading to a reduction in the wage, labor supplied, and ultimately the size of the economy.

Figure 3: 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.

However, it is important to note that, after a carbon tax policy is adopted, the factor prices, and the resulting levels of capital, hours, and consumption, may not immediately adjust to the new steady state levels. A key advantage of our model is that we are able to

compute the equilibrium factor prices during the transition to the new steady state. For each of the carbon tax policies, the first row of panels in Figure (3) plots the transition paths for the after-tax wage and after-tax risk-free rate during the first 100 years following the adoption of the tax policy. For comparison, we plot the percentage changes in the after-tax wage and risk-free rate relative to the baseline steady state without the carbon tax.

The results presented in Figure (3) 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 due to varying fluctuations in the firm's demand for the different inputs. 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 6). 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. The second row of panels in Figure (3) 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 3). 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.

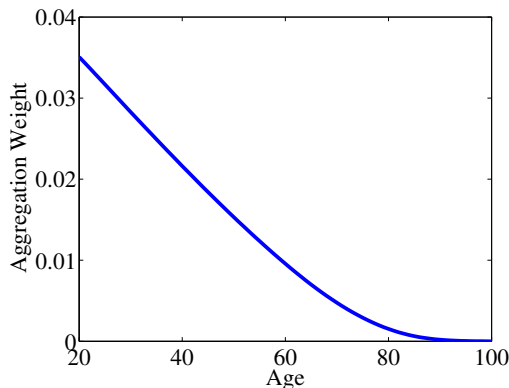
The differences in the short-term and long-run factor price changes displayed in Figure (3) suggest that the non-environmental welfare effects of a carbon tax policy may be quite different in the short-run versus in the future long-run steady state. Figure (3) also reveals that, while the immediate factor price responses can differ meaningfully from the long-run responses, the factor prices effectively reach their new long-run levels in a fairly short period of time – approximately 40 years. This suggests that if the non-environmental welfare effects will differ meaningfully across the short- and long-runs, then this would largely be seen within the agents already alive at the time the carbon-tax policy is adopted (i.e. the living population). In addition to facing potentially very different factor prices, agents alive at the time the policy is adopted may also experience different non-environmental welfare effects due to the fact that they only experience the carbon tax policy for a portion of their life cycle. The subsequent analysis focuses on how agents living at the time the policy is enacted are affected by a carbon tax.

To analyze the welfare consequences for the living population, we calculate the CEV in terms of the cohort's expected future consumption over the portion of their life cycle following the government's introduction of the policy. For example, to calculate the welfare effects of the policy for a cohort who is 25 when the tax is introduced, we compute the uniform percent change in consumption across all agents in the cohort that would be necessary, in every remaining period of their lifetime, 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 over the transition is the weighted average of the CEVs for the different age cohorts. We determine the weight for each age cohort based on the present discounted value of remaining lifetime consumption for the cohort relative to the total present discounted value of remaining lifetime consumption for all age cohorts in the economy. The remaining lifetime consumption is relatively higher for the younger cohorts because in expectation they have more remaining years of life and because the younger cohorts contain

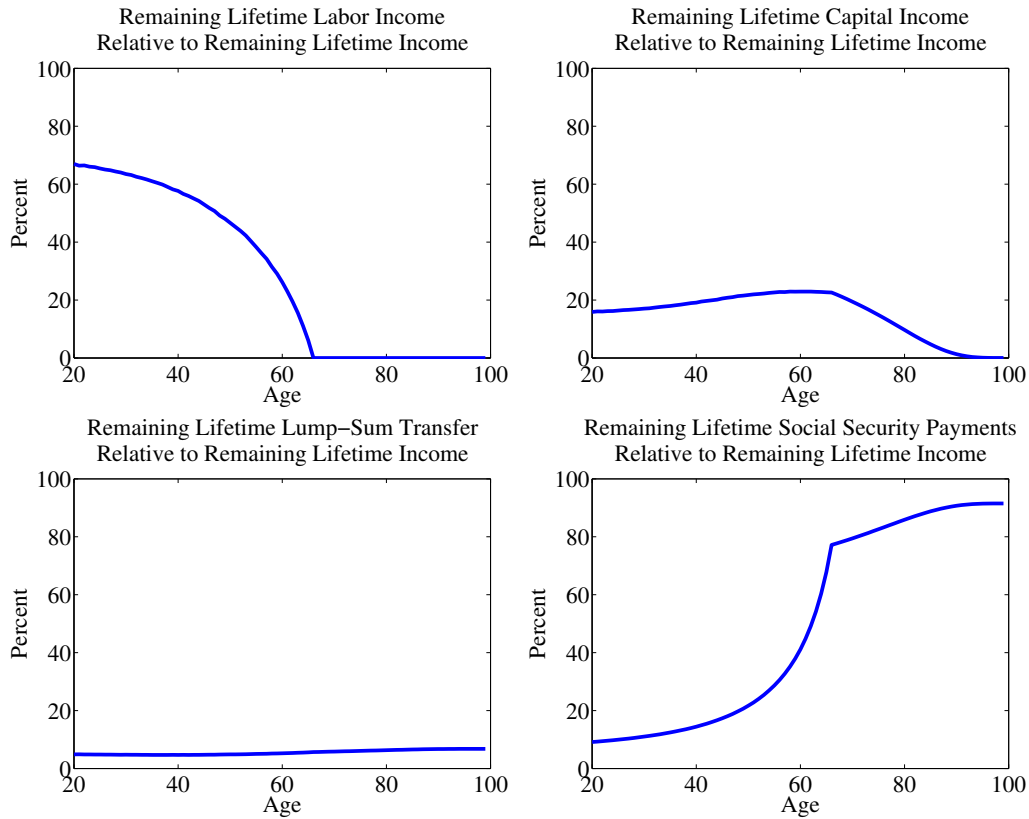
relatively more people. As a result, our aggregation method places considerably more weight on the younger generations. Figure 4 plots the aggregation weights for each age cohort.

Figure 4: Aggregation Weight For Each Age Cohort



The second row of Table 5 reports the aggregate welfare effects of the carbon tax policies on the agents alive at the time the policies are implemented. Comparing the first and second rows of Table 5 we see that, under the capital and labor tax rebate policies, agents alive at the time the policy is adopted fare worse than agents born into the future steady state. Within the living population, the capital tax rebate policy leads to an average CEV of only 0.06 – approximately one fifth as large as the expected increase in non-environmental welfare in the steady state. Under the labor tax rebate policy, the living population experiences an average CEV of -0.63 – almost twice as large as the expected non-environmental welfare decline experienced by agents born into the steady state. In contrast, under the lump-sum rebate, agents alive at the time the policy is adopted are better off than those born into the future steady state. While the average steady state CEV was -1.26 under the lump-sum rebate policy, the CEV among the living population is 0.26. That is, adopting a carbon tax with uniform lump-sum rebates increases the non-environmental welfare of the living population, which is in stark contrast to the long-run impacts.

Figure 5: Share of Remaining Lifetime Income by Source

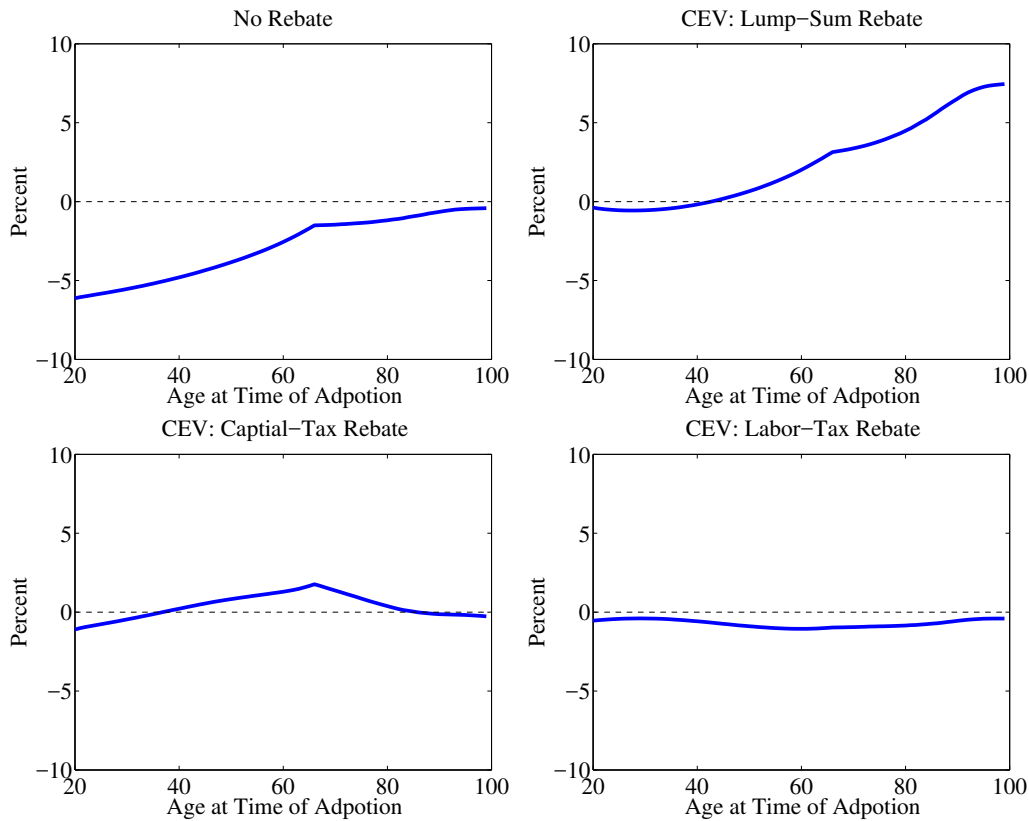


Note: The figure shows the average share of remaining lifetime income from particular sources of income for each age cohort. Starting at the top left panel and moving clockwise, the figure displays the average share of remaining lifetime income from labor income under the labor-tax rebate policy, from 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 differences in the aggregate welfare effects between the steady state and the transition are largely explained by the movements in factor prices during the early transition years. The welfare consequences of these initial factor price changes depend critically on the relative importance of income from capital, labor, lump-sum transfers, and Social Security, which, in turn, depend on the agent's age when the government introduces the policy. Figure 5 plots remaining lifetime income from labor, capital, lump-sum transfers, and Social Security relative to remaining lifetime income for each age cohort. Intuitively, the labor income share of remaining lifetime income falls and Social Security income share of remaining lifetime

income rises as the cohort ages and, thus, has fewer remaining working years. The capital income share of remaining lifetime income rises throughout working life as agents accumulate savings and then falls as agents deplete their savings during retirement. The transfer income share of remaining lifetime income is relatively constant 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 6: 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.

The movements in factor prices (Figure 3) combined with the age-dependent shares of remaining lifetime capital, labor, and transfer income imply that the welfare consequences of a carbon tax policy can vary considerably with the cohort's age when the government

introduces the policy. To highlight this variation over the life cycle, Figure 6 plots the average non-environmental welfare effects conditional on the agent's age at the time a carbon tax policy is adopted.

The upper left panel of Figure 6 displays the CEV by age in the case where carbon tax revenues are not rebated. Recall from Figure 3, in the no-rebate case, the after-tax wage experiences an immediate, and sizable, decrease. The decrease in the after-tax wage harms the youngest agents the most since the majority of their remaining lifetime income comes from labor (see Figure 5). In contrast, agents that have already retired at the time the carbon tax is implemented are largely unaffected by the policy. Those that have recently retired, and therefore still receive a large share of income from capital, experience a small welfare decline due to the small decrease in the after-tax returns to capital. The very oldest cohorts, who depend heavily on Social Security transfers, are almost completely unaffected by the carbon tax. This is due to the fact that the Social Security benefits adjust in response to changes in the total cost of energy – including taxes – in order to keep the purchasing power of the benefits the same.²⁸ Given that the no-rebate policy is less costly for the older living generations, the CEV is only -4.65 among the living population, as opposed to -6.47 in the future steady state.

From the top right panel of Figure 6, it is clear that while the lump-sum rebate imposes slight costs on younger cohorts, it creates substantial welfare gains for the older living cohorts. These older agents receive little (or no) remaining lifetime income from labor, and therefore, they do not suffer as much from the decline in the after-tax wage (bottom right panel of Figure 3). While these agents are harmed slightly by the small initial decline in the after-tax risk free rate (bottom left panel of Figure 3), this effect is dominated by the welfare gains from the lump-sum transfer. These benefits for the older agents are so large that the lump-sum rebate is welfare improving for the aggregate living population.

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

²⁸As prior research has noted (Fullerton et al. (2012) and Blonz et al. (2012)), this practice insulates the elderly from climate policy.

bottom left panel of Figure 6 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 5). 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 5), 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 6) 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 the higher welfare costs for middle-aged agents are not offset by the lower costs for younger agents, as they are in the steady state.

4.3.2 Transition: Distribution of welfare effects by income quintile

In this section, we examine how the distributional impacts of the carbon tax policies differ in the transition versus the future steady state. The top panel of Table 9 reports the CEV by income quintile for each tax policy. The bottom row reports the percent change in the Gini coefficient compared to the baseline value in which no carbon tax is adopted.²⁹ Over the transition, the population value of the Gini coefficient is a weighted average of the Gini coefficient for each cohort where the weights are determined by the relative population shares. We calculate the Gini coefficient for a given age cohort from each household's remaining

²⁹Note that the baseline value of the Gini coefficient over the transition varies slightly from the steady state baseline value (0.13 compared to 0.15) because it is a weighted average of the Gini coefficient for the remainder of the living population's life cycles in the baseline. In contrast, we calculate the steady state baseline value of the Gini coefficient from the expected lifetime welfare of each individual, beginning at birth.

lifetime welfare. For example, for households who are 25 when the government introduces the policy, we calculate the Gini coefficient in the baseline and the transition from expected remaining lifetime welfare starting at age 25.

Just as we found in the steady state, during the transition, 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 8 and Table 9), 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.

Table 9: Transition: Welfare Effects For the Living Population: Distribution

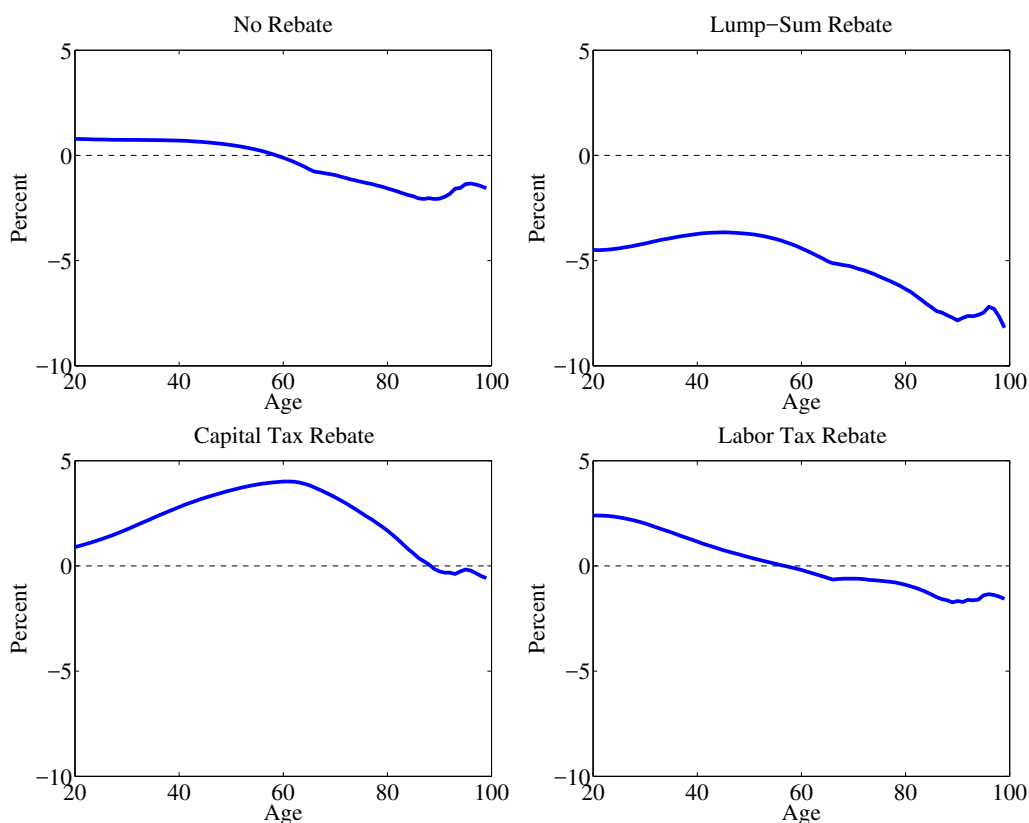
	No Rebate	Lump-sum Rebate	Capital Tax Rebate	Labor Tax Rebate
CEV (percent)				
Quintile 1	-4.77	2.10	-0.86	-1.18
Quintile 2	-4.67	0.60	-0.20	-0.72
Quintile 3	-4.61	-0.22	0.33	-0.48
Quintile 4	-4.56	-0.99	0.77	-0.23
Quintile 5	-4.50	-1.85	1.29	0.00
% $\Delta \mathcal{G}$ From Baseline Value of 0.15	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

To understand why the distributional impacts differ in the transition relative to the steady state, Figure 7 plots the percent change in the Gini coefficient for the different age groups.³⁰ Focusing first on the upper-left panel, the no-rebate case, the percent change in the Gini coefficient across age cohorts is initially flat and slightly positive – demonstrating that the carbon tax is slightly regressive within the youngest cohorts. Again, this is driven largely by the inherent regressivity of the carbon tax – low income agents spend the largest share of their expenditures on energy. However, among the cohorts nearing or post-retirement, the Gini

³⁰For reference, Figure 11 in the Appendix plots the level Gini coefficient for each age cohort in the baseline.

coefficient falls in the no-rebate case. Recall, under the no-rebate policy, the after-tax risk-free rate experiences a sizable and immediate drop. This decrease in the returns to capital disproportionately harms the wealthiest agents that have accrued the most savings, making the no-rebate policy progressive within the older living cohorts.³¹ As a result, aggregating across all living age cohorts, the no-rebate policy ends up being less regressive compared to the future steady state distributional impact.

Figure 7: 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.

³¹This progressive effect during the later years of the life cycle does not affect the younger living age cohorts. By the time the younger cohorts have aged and accrued larger capital savings, the after-tax risk-free rate recovers to a level slightly above the initial baseline steady state.

Under the labor tax rebate, the percent change in the Gini coefficient decreases steadily with age (bottom right panel of Figure 7) causing the labor-tax rebate to be more progressive over the transition. This pattern is again 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.

Under the capital tax rebate (bottom left panel of Figure 7), the percent change in the Gini coefficient is positive across nearly every age cohort alive at the time the policy is adopted. The 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 back closer to the long-run 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.

Under the uniform lump-sum rebate policy (top right panel of Figure 7), the percentage change in the Gini coefficient is negative across all age cohorts. Again, the transfer received by each agent is independent of their income. As a result, lower income agents receive a larger percentage increase in their total income, making the policy progressive. This progressive effect is the most pronounced among the oldest age cohorts who receive the largest share of their remaining income from the transfers. In contrast to the labor or capital tax rebate policies, however, there is little difference between the progressivity of the lump-sum rebate policy in the short-term versus in the future long-run steady state.

5 Robustness

5.1 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.³² Therefore, assuming an exogenous energy price likely does not represent an extreme simplification. 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. However, the subsequent analysis reveals that the pattern of results from the model presented in Section 4 are effectively unchanged with the inclusion of an endogenous energy price.

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

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

where subscript “1” denotes inputs used in the final good sector and subscript “2” denotes

³²Recall, in our simulations, U.S. energy consumption falls by approximately 15 percent. In 2012, U.S. carbon-energy use accounted for 16 percent of global carbon-energy use. Therefore, the predicted reduction in U.S. energy consumption would only represent a 2 to 3 percent decrease in global fossil energy demand.

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.³³ 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 5), 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 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
Transition	-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

³³This is similar to the value of 0.03 used by Barrage (2016) and Golosov et al. (2014).

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: Transition Welfare Effects 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

5.2 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 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. 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 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 5), 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 8 and 9), 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: Transition Welfare Effects 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

6 Conclusion

Imposing a carbon tax could potentially affect welfare not only through environmental channels, but also through non-environmental channels by causing large, general equilibrium impacts throughout the economy. Previous works in the environmental and public economics literatures highlight that the way in which carbon tax revenue is used can dramatically alter

the resulting non-environmental welfare costs. In particular, previous studies demonstrate 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 to households 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.

In this paper, we examine the welfare and distributional impacts various revenue-neutral carbon tax policies would have not only in the long-run steady state, but also during the transition to the new steady state. To do so, we construct a quantitative, overlapping generations model which incorporates within age cohort income heterogeneity. Using the model, we explore the welfare consequences of imposing a \$35 per ton tax on CO₂. 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. By studying the impacts of carbon tax policies in a life cycle model which includes within cohort heterogeneity, we are able to examine how the welfare effects differ not only with age, but also with income.

Our results reveal that the non-environmental welfare effects of revenue-neutral carbon tax policies can differ substantially between agents who are alive when the policy is enacted and agents who are born into the new, long-run steady state. Consistent with previous studies, we demonstrate that, for those born in the new steady state, the expected non-environmental welfare costs are minimized when the carbon tax revenue is used to reduce a pre-existing distortionary tax as opposed to being returned in the form of lump-sum payments. However, we find that, during the transition, the welfare costs incurred by recycling carbon tax revenues to reduce labor or capital taxes are substantially larger. In fact, our results suggest that, during the transition, the non-environmental welfare costs are not necessarily larger when the carbon revenues are recycled as lump-sum payments. In addition, our results show that certain revenue-neutral carbon tax policies can be more regressive

during the transition than in the steady state.

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 to enact the policy are the also the ones who 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 costs and regressivity of the policy.

Our analysis focused on the three most widely discussed rebate options for carbon tax revenue in the environmental 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 often 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.

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A Additional Results

A.1 Steady state

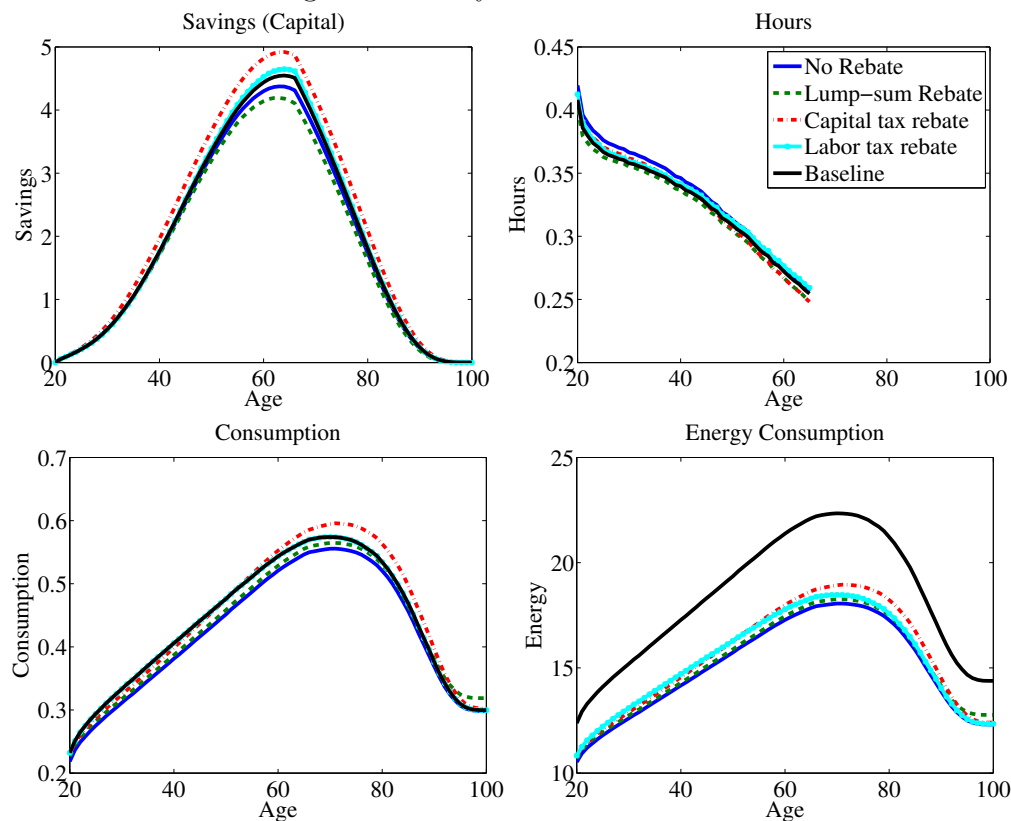
Section 4.2 discusses the impact of each carbon tax policy on the steady state values of aggregate capital, labor, consumption, and energy usage. To examine how an individual agent’s capital savings, hours worked, consumption, and energy consumption vary over the life cycle in the steady state, Figure 8 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 9 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, 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 9). 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 9). 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.

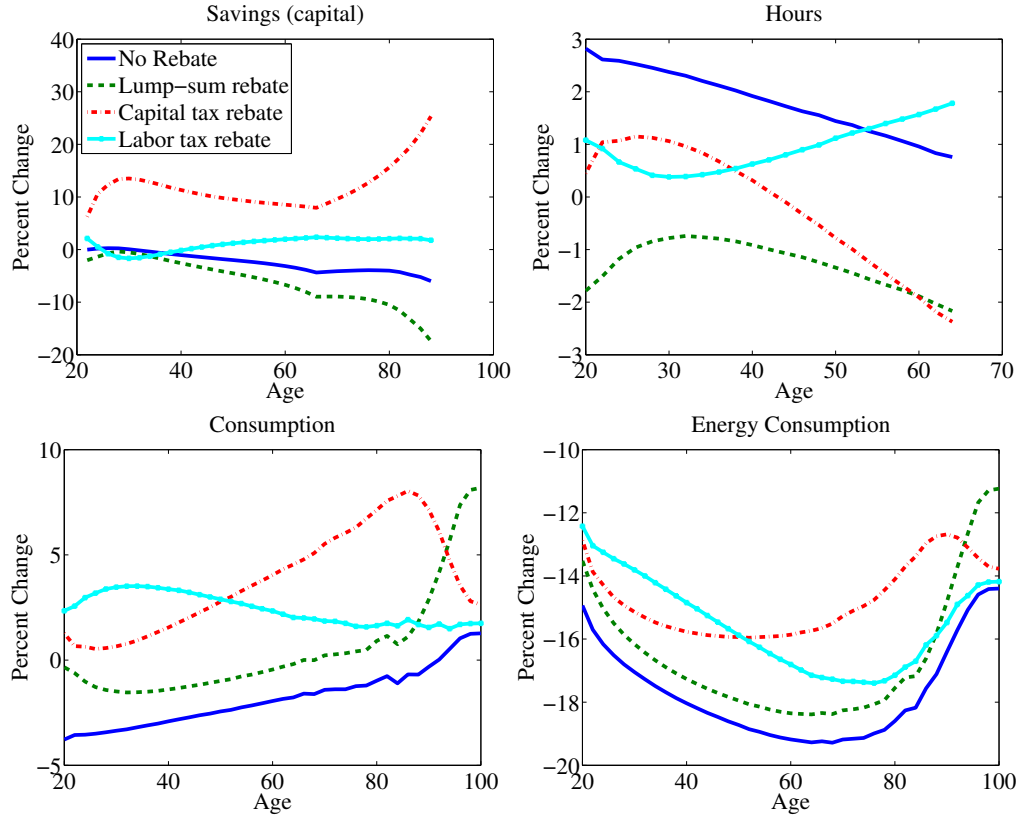
Finally, in all four simulations, energy use is lower in every period of the life cycle because the carbon tax raises the relative price of energy (bottom right panel of Figure 9). This change in energy consumption is generally largest for the middle-aged agents. The level of energy consumption is highest for this age group, implying that their energy demand is the most elastic.

Figure 8: 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 9: Lifecycle Profiles: Percent Change From Baseline



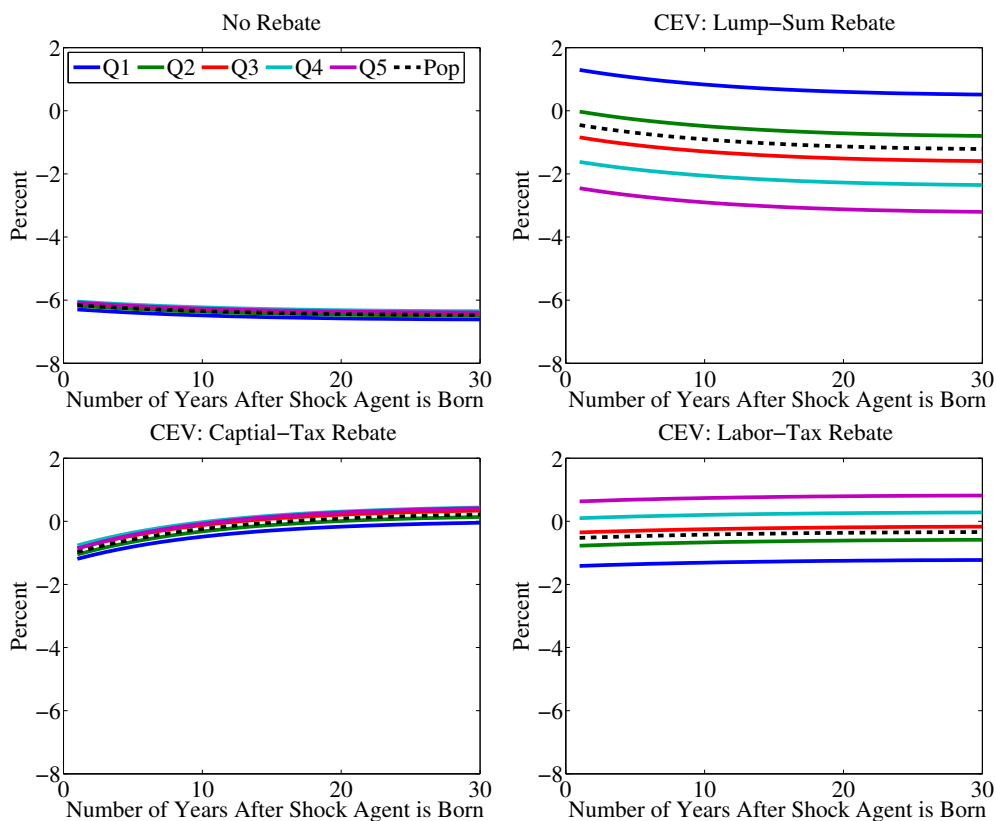
Note: The figure plots the percent change under the carbon tax policy from the baseline case in the average savings, hours, consumption and energy consumption for each age cohort. The profiles are in the steady state.

A.2 Transition

The discussion in Section 4.3 focused on the non-environmental welfare effects of the carbon tax policies on agents alive when the policy was introduced. We now turn to the welfare effects among agents who are born after the shock is introduced, but before the economy has fully transitioned to its new steady state. Figure 10 reports the CEV for agents born during the transition, but after the policy is adopted. In all cases, the welfare effects converge to the steady state results as the number of years after the shock that the agent is born increases. Under the no rebate, lump-sum, and labor tax rebates, welfare changes relatively little as the economy approaches its new steady state. However, under the capital-tax rebate, welfare

increases steadily as the economy transitions. The capital tax rebate leads to a comparatively large accumulation of capital (Figure 3), increasing the wage rate and, thus, welfare over the transition.

Figure 10: Transitional Welfare for Newborn Agents

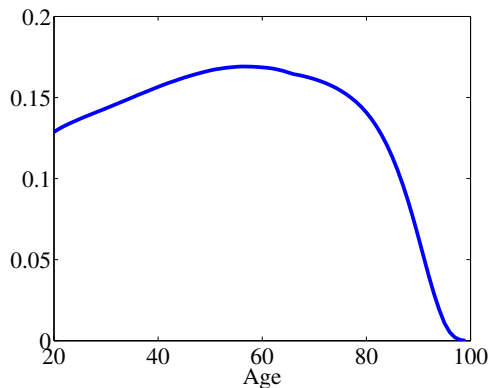


Note: The figure plots the welfare effects of adopting each carbon tax policy for cohorts who enter the model after the tax policy is adopted. The different lines show the welfare effects income quintiles where the quintiles are measured in terms of the lifetime expenditures the agent would have had if the policy had not been adopted.

Finally, the discussion in Section 4.3 reported the magnitude of the distributional effects for each age cohort by calculating the percent change in the Gini coefficient relative to its value in the baseline for the specific age cohort. For reference, Figure 11 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.

Figure 11: 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.

B 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.³⁴ 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).

³⁴See Heer and Maussner (2009).

4. Compute the value function for agents on the state space of ability, idiosyncratic shocks, savings and age using backward induction.³⁵
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 his 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.
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 100.³⁶
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).

³⁵We discretize the savings grid and interpolate the value function between savings grid points.

³⁶We check whether this is a sufficient number of periods and find that the transition occurs in substantially less than 100 periods.

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 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 his 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.