The Macro Effects of Anticipating Climate Policy

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Abstract

While the U.S. does not currently have a federal carbon tax, households could expect the government to introduce a carbon tax policy in the future. To understand how the macroeconomy responds to the expectation of a potential future carbon tax, we develop a quantitative life cycle model that allows us to focus on investment in long-lived, sector-specific assets such as coal power plants or wind farms. We find that expectations of future climate policy reduce the return dirty (carbon-emitting) energy capital, shifting the economy towards cleaner energy production. As a result, the anticipation of future climate policy reduces carbon emissions even though there is not actual policy in place. In particular, we find that a five percent probability of a \$35 dollar per ton carbon tax reduces emissions by one quarter of the amount they would fall if the carbon tax was actually in place. However, the output cost of reducing emissions through expectations of future policy are considerably higher than the output cost of the carbon tax policy itself. This is because the potential costs of reallocating capital between energy producing technologies after the tax is implemented, such as from coal power plants to wind farms, along with the uncertainty depresses savings lowering the aggregate capital stock.

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1 Introduction

Imposing a tax on carbon emissions has the potential to provide large welfare gains through environmental channels – e.g., reducing the risks posed by climate change and improving air quality. In addition, a carbon tax would 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. To provide insights into the welfare and distributional effects of adopting a carbon tax, a large literature employs a range of general equilibrium models to compare outcomes in two different states of the world: a future with a carbon tax versus the current state with no carbon tax.[1]

In practice however, modeling the current state of the world is not so simple. While the U.S. does not currently have a federal climate policy, that does not mean that individuals and firms are proceeding as though there will never be a federal climate policy. Recent surveys demonstrate that a majority of U.S. adults support increasing energy prices to combat climate change.[2] Moreover, several federal climate policy proposals were nearly adopted over the past decade (e.g., Waxman-Markey, the Clean Power Plan). Given the base of public and political support, there is widespread awareness that a climate policy may be adopted at some point in the future. Seeing as capital investments tend to be long lived, the anticipation of a potential carbon tax could significantly impact the economy well before any policy is ever proposed or enacted.

In this paper, we explore the macroeconomic impacts stemming from the anticipation of a potential carbon tax policy at some unknown, future date. Using a quantitative overlapping generations model calibrated to the U.S. economy, we find that, even with a fairly modest probability placed on a carbon tax being adopted, the aggregate levels of capital, labor, consumption, and energy use are distorted away from the levels that would prevail in a

[1] For example, see Parry et al. (1999), Rausch et al. (2011), and Williams et al. (2015).

[2] For example, a 2016 survey completed by the Energy Policy Institute at the University of Chicago and The AP-NORC Center for Public Affairs Research found that 65% of Americans believe climate change is a problem the federal government should address and 57% would support paying higher energy bills to do so.

world with zero chance of enacting a carbon tax or even the world with an established carbon tax. The anticipation effects are quantitatively significant. Moreover, they do not move the economy uniformly towards the steady state outcome that would occur under a carbon tax. Instead they distort individuals' labor, consumption, and savings, decisions in ways that differ from the long run responses to a carbon tax.

To study the impacts of anticipating a carbon tax, we build on the quantitative OLG model introduced by Fried et al. (2018). We extend this earlier model to include clean and dirty energy inputs, endogenous energy production, and sector-specific capital. Using the model, we compare the steady state outcomes in three different states of the world. One in which there is no possibility of a tax being implemented. One with a revenue-neutral carbon tax policy in place. And finally, one in which there is a small, constant probability of a revenue-neutral carbon tax policy being implemented in the subsequent period.[3]

Importantly, the model incorporates two key mechanisms through which the anticipation of a carbon tax could the affect agents' decisions to consume, work, and save. First, we incorporate the potential for stranded assets by assuming that if there is a reduction in the aggregate level of a particular type of capital, only a portion is salvageable in the new technology for which it is used. Given this friction, forward looking agents may alter the portfolio of capital assets in which they choose to invest in anticipation of a future carbon tax. Second, by modeling agents' decisions over the life cycle, we allow the anticipation effects to vary based on an agent's age. These age specific responses can arise for two reasons. For one, younger agents face a higher likelihood of experiencing a carbon tax at some point in their future. Second, individuals' sources of income vary substantially over the life cycle. As a result, a potential future carbon tax could illicit a very different response among young agents compared to older agents. For example, suppose that a carbon tax would cause the

[3]Uncertainty surrounding the timing of future policy changes has been studied using dynamic GE models in different settings. For example, Caliendo et al. (2015) and Kitao (2018) study the impact of uncertainty surrounding future reforms to social security policies. Uncertainty surrounding future productivity has also been explored using quantitative OLG models (e.g., Hasanhodzic and Kotlikoff (2013)). Within the environmental literature, Xepapadeas (2001) and Pommeret and Schubert (2017) consider the effect of policy uncertainty on firms' investment and location decisions. However, these previous studies do not focus on the general equilibrium impacts of environmental policy uncertainty.

wage to fall. While young agents may increase hours worked and savings to partially insure against this potential future negative labor-income shock, retired agents, or those close to retirement, would be largely unaffected by the threat of a future wage decrease.

Comparing the three steady state outcomes – (1) in a world with no possibility of a future carbon tax (initial equilibrium), (2) in a world with a positive probability of a carbon tax being adopted in the subsequent period (stochastic equilibrium), and (3) in a world with a revenue-neutral carbon tax policy in place (final equilibrium) – we find several important patterns. Intuitively, we find that compared to the simplistic case with zero probability of a carbon tax being adopted, adopting a carbon tax alters the mix of capital – e.g., the ratio of dirty to clean capital falls. As a result, there is a large reduction in emissions (i.e. consumption of the dirty energy input) with a relatively small reduction in total output.

A comparison to the steady state in a world with no possibility of a tax versus the steady state in a world in which agents place a positive probability on a tax being adopted in the subsequent period reveals a very different pattern. In particular, agents internalizing the probability of a future carbon tax results in a reduction in the ratio of dirty to clean capital, reducing carbon emission. However, because the enactment of the carbon tax will lead to scrapping of resources (particularly dirty capital), the anticipation of the tax depresses overall investment. The depressed investment across all types of capital means that the reduction in emissions is accompanied by a relatively large reduction in output.

Our findings have two key implications. First, in terms of reducing emissions, both the expectation of a future carbon policy and the tax itself will lead to reductions in dirty energy use relative to the world where there is no potential for a carbon tax. Importantly however, imposing the carbon tax can achieve a given reduction in dirty energy consumption at a much smaller cost (in terms of reductions in total output). Relative to the state in which there is no possibility of a carbon tax being adopted, imposing a carbon tax only reduces total output by 0.05 percent per each 1 percent reduction in emissions. In contrast, 0.62 percent of total output is reduced for each 1 percent reduction in emissions caused by the expectation of a carbon tax. In essence, the threat of a future carbon tax serves as a very costly climate policy.

Our findings also have important implications for understanding the effect of adopting a carbon tax. To predict the macroeconomic impacts of adopting a carbon tax, the existing literature implicitly assumes that we are starting from a state of the world where agents do not expect a future carbon policy. In line with our findings, these previous studies consistently conclude that adopting a carbon tax will reduce total output. However, if the current state of the world is more accurately reflected by our stochastic steady state in which agents have internalized the positive probability of a future climate policy, then the adoption of a carbon tax could in fact lead to a meaningful increase in total output – all while still inducing meaningful reductions in dirty energy usage.

2 Model

The model builds off the framework developed in Fried et al. (2018). We extend this earlier model to include clean and dirty energy inputs, endogenous energy production, and sector-specific capital. To simplify the model in Fried et al. (2018), we analyze a representative agent in each age-cohort; there is no within-cohort income heterogeneity. We describe each component of the model in turn.

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. All agents are forced to retire at the exogenously determined age j^r.

2.2 Production

The economy has three sectors: (1) clean energy, (2) dirty energy, and (3) the final good. Dirty energy refers to energy derived from coal, oil, or natural gas. Clean energy refers to energy derived from any non-carbon energy source, such as solar or wind. A measure one of perfectly competitive firms produces in each sector.

The final good is produced from final-good capital, K^y, labor, N^y (measured in efficiency units), and energy, E^y, according to the CES production function,

$$Y_t = A^y \left[\left((K_t^y)^{\alpha_y} (N_t^y)^{1-\alpha_y} \right)^{\frac{\phi_y - 1}{\phi_y}} + (E_t^y)^{\frac{\phi_y - 1}{\phi_y}} \right]^{\frac{\phi_y}{\phi_y - 1}}, \tag{1}$$

where $\phi_y < 1$ is the elasticity of substitution between the capital-labor composite and energy. Variable A^y denotes total factor productivity in final good production. Energy is a nested CES composite of clean, E^c, and dirty, E^d, energy inputs,

$$E_t^y = \left[(E_t^c)^{\frac{\phi_e - 1}{\phi_e}} + (E_t^d)^{\frac{\phi_e - 1}{\phi_e}} \right]^{\frac{\phi_e}{\phi_e - 1}}. \tag{2}$$

Parameter $\phi_e > 1$ denotes the elasticity of substitution between clean and dirty energy. The final good is the numeraire.

Clean and dirty energy are produced competitively and sold at market prices. The production functions for each energy type are constant returns to scale in capital, K^q, and labor, N^q (measured in efficiency units), for $q \epsilon \{c, d\}$,

$$E_t^c = A^c (K_t^c)^{\alpha_e} (N_t^c)^{1-\alpha_e} \quad \text{and} \quad E_t^d = A^d (K_t^d)^{\alpha_e} (N_t^d)^{1-\alpha_e}. \tag{3}$$

Variables A^c and A^d denote total factor productivity in clean and dirty energy, respectively, and parameter α_e is capital's share in energy production. Carbon emissions are proportional to the amount of dirty energy production. Thus, policymakers can reduce carbon emissions by reducing the amount of energy production in the dirty sector.

2.3 Households

A household is endowed with one unit of productive time per period that can be divided between labor and leisure. In period t, at age j, agent i earns labor income $y^n_{i,j,t} \equiv w_t \cdot \varepsilon_j \cdot h_{i,j,t}$, where w_t is the market wage, $h_{i,j,t}$ denotes hours worked, and ε_j is the agent's age-specific human capital. Households save by purchasing shares, $a_{i,j,t+1}$, from a capital-intermediary with rate of return r.

Households have time-separable preferences over consumption, $c_{i,j,t}$, and hours, $h_{i,j,t}$. The utility function is given by

$$U(c_{i,j,t}, h_{i,j,t}) = \frac{c_{i,j,t}^{1-\theta_1}}{1-\theta_1} - \chi \frac{h_{i,j,t}^{1+\frac{1}{\theta_2}}}{1+\frac{1}{\theta_2}}. \tag{4}$$

This functional form is separable and homothetic in the consumption and hours, implying a constant Frisch elasticity of labor supply, regardless of hours worked.

2.4 Capital Intermediary

An important concern surrounding the introduction of climate policy is that it could lead some assets, particularly those used to produce dirty energy, to be stranded. That is, these assets could suffer from a large and immediate drop in value when the government introduces the policy. To incorporate this friction, we assume that capital investment is sector-specific and that capital is not fully fungible across sectors. For example, a wind turbine is used to produce clean energy while a coal boiler is used to produce dirty energy. If the aggregate level of investment in any sector q, is negative, $I^q_t < 0$, then the dis-invested capital is sold for its scrap value $(1-\lambda)|I^q_t|$ and then converted to capital in a different sector or to final good. Value $\lambda|I^q_t|$ is the aggregate scrapping cost of the capital (Ramey and Shapiro (1999); Ramey and Shapiro (2001); Clementi et al. (2014)). The average scrapping cost per unit of capital, Λ_t^q is,

$$\Lambda_t^q = \begin{cases} \frac{\lambda |I^q|}{K_t^q} & : I_t^q < 0 \\ 0 & : \text{otherwise} \end{cases}$$

where variable K_t^q denotes the aggregate level of capital in sector q.

The capital intermediary chooses this period's investment, and hence next period's level of capital, in each sector. Specifically, at the end of period t, the intermediary allocates the household funds across the three types of capital, K^c, K^d, and K^y, to maximize the average rate of return, r,

$$r = \left(\frac{K^y}{K}\right) r^y + \left(\frac{K^c}{K}\right) r^c + \left(\frac{K^d}{K}\right) r^d, \tag{5}$$

where $K = K^y + K^c + K^d$ is the aggregate level of capital in the economy. Variables r^y, r^c and r^d denote the rates of return to non-energy, clean, and dirty capital, respectively.

The period t rate of return to sector-q capital, r_t^q, is composed of three parts. First, at the start of period t, the intermediary rents the capital to firms at rate $R_t^q K_t^q$. The intermediary chooses R_t^q so that the firms' sector-q capital demand equals the intermediary's supply. Second, the capital incurs a depreciation cost, δK_t^q. And third, the intermediary incurs a scrapping cost if it chooses to disinvest in sector q, $\Lambda_t^q K_t^q$. Thus, the net rate of return to capital in sector q is

$$r^q = R^q - \delta - \Lambda^q. \tag{6}$$

At the end of period t, the intermediary pays each household the average rate of return on her assets and returns the assets back to the household. Thus household i age j receives, $(1 + r_t)a_{i,j,t}$, at the end of period t.

2.5 Government Policy

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

The government taxes each agent's capital income, $y_{i,j,t}^k$, according to a constant marginal tax rate, τ^k. An agent's capital income is the return on her assets plus the return on any assets she receives as accidental bequests, $y_{i,j,t}^k \equiv \sum_{q \epsilon \{c,d,y\}} r_t^q (a_{i,j,t}^q + T_t^{aq})$. The government taxes labor income according to a progressive tax schedule, $T^n(\tilde{y}_{i,j,t}^n)$, where $\tilde{y}_{i,j,t}^n$ denotes the agent's taxable labor income. A working agent's taxable labor income is her labor income, $y_{i,j,t}^n$, net of her employer's contribution to Social Security which is not taxable under U.S. tax law. Thus, $\tilde{y}_{i,j,t}^n \equiv y_{i,j,t}^n(1 - \tau_t^s/2)$, where $(\tau_t^s/2)y_{i,j,t}^n$ 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 $T^s(S_t, y_{i,j,t}^n)$.

Finally, the government can tax dirty (carbon) energy at a constant rate. This tax not only raises government revenue, but it can also reduce the use of carbon based energy. The carbon tax, τ^d, is designed to place a price on the externality, carbon. Thus, the government applies the tax per unit of energy consumed, raising the price of dirty energy from p^d to $p^d + \tau^d$.[4] The government rebates this carbon-tax revenue through uniform

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

lump-sum transfers to the households, T^d_t.

2.6 Deterministic Stationary Equilibrium

Our focus is on the effects of policy uncertainty. Our main approach will be to compare a stationary equilibrium without policy uncertainty (deterministic equilibrium), to a stationary equilibrium with policy uncertainty (stochastic equilibrium). We begin by describing the deterministic equilibrium. In Section 2.7 we extend this description to define the stochastic equilibrium.

In each period in the deterministic equilibrium the household chooses labor, generic consumption, clean and dirty energy consumption, and savings, to maximize expected lifetime welfare,

$$V(a_{ij}; j) = \max_{(a_{ij})', h_{ij}, c_{ij}} u(c_{ij}, h_{ij}) + \beta \Psi_j V((a_{ij})'; j+1), \tag{7}$$

subject to her age-specific budget constraint,

$$\begin{aligned} & c_{ij} + (a_{ij})' = \\ & \quad \mu h_{ij} w(1-\tau^s) + (1 + r(1-\tau^k))(a_{ij} + T^{aq}) - T^n\big(\mu h_{ij} w(1 - .5\tau^s)\big) + T^c \quad \text{for } j < j^r \end{aligned} \tag{8}$$

$$c_{ij} + (a_{ij})' = S - T^s(S, y^n_{ij}) + (1 + r(1-\tau^k))(a_{ij} + T^{aq}) + T^c \quad \text{for } j \geq j^r \tag{9}$$

and the non-negativity constraints,

$$c \geq 0,\ 0 \leq h \leq 1,\ a \geq 0,\ a_{20} = 0 \tag{10}$$

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

We define a stationary competitive equilibrium with no policy uncertainty. In the long-run steady state, the factor prices, tax parameters, and aggregate macroeconomic variables will be constant. The individual state variables, x, are asset holdings in each sector q, a^q, and age j. In addition, we signify an agent's chosen level of sector-specific capital savings in the subsequent period as $(a^q)'$. 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, $T^n : \mathbb{R}_+ \to \mathbb{R}_+$, a capital-tax rate, τ^k, a carbon-tax rate, τ^d, transfers from the climate policy, T^d, a utility function $U : \mathbb{R}_+ \times \mathbb{R}_+ \times \mathbb{R}_+ \to \mathbb{R}_+$, factor prices, $\{w,\ r^c,\ r^d,\ r^y,\ p^c,\ p^d\}$, a stationary competitive equilibrium consists of agents' decisions rules, $\{c, h, (a^c)', (a^d)', (a^y)'\}$, firms' production plans, $\{E^c, E^d, K^c, K^d, K^y, N^c, N^d, N^y\}$, transfers from accidental bequests $\{T^{ac},\ T^{ad},\ T^{ay}\}$, 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, the agent maximizes equation (7) subject to equations (8) - (10).

2. The capital intermediary chooses $(K^y)'$, $(K^d)'$, and $(K^c)'$ to maximize the average rate of return, equation (5), subject to the constraint that total household assets must equal the total capital stock,

$$\sum a'\Phi(x) = (K^y)' + (K^c)' + (K^d).' \tag{11}$$

3. The representative final good firm's demand for K^y, N^y, E^c, and E^d satisfy:

$$p^c = A^y \left[\left((K^y)^{\alpha_y} (N^y)^{1-\alpha_y} \right)^{\frac{\phi_y - 1}{\phi_y}} + (E^y)^{\frac{\phi_y - 1}{\phi_y}} \right]^{\frac{1}{\phi_y - 1}} (E^y)^{\frac{-1}{\phi_y}} \left[(E^c)^{\frac{\phi_e - 1}{\phi_e}} + (E^d)^{\frac{\phi_e - 1}{\phi_e}} \right]^{\frac{1}{\phi_e - 1}} (E^c)^{\frac{-1}{\phi_e}}$$

$$p^d + \tau^d = A^y \left[\left((K^y)^{\alpha_y} (N^y)^{1-\alpha_y} \right)^{\frac{\phi_y - 1}{\phi_y}} + (E^y_t)^{\frac{\phi_y - 1}{\phi_y}} \right]^{\frac{1}{\phi_y - 1}} (E^y)^{\frac{-1}{\phi_y}} \left[(E^c)^{\frac{\phi_e - 1}{\phi_e}} + (E^d)^{\frac{\phi_e - 1}{\phi_e}} \right]^{\frac{1}{\phi_e - 1}} (E^d_t)^{\frac{-1}{\phi_e}}$$

$$w = A^y \left[\left((K^y)^{\alpha_y} (N^y)^{1-\alpha_y} \right)^{\frac{\phi_y - 1}{\phi_y}} + (E^y)^{\frac{\phi_y - 1}{\phi_y}} \right]^{\frac{1}{\phi_y - 1}} \left((K^y)^{\alpha_y} (N^y)^{1-\alpha_y} \right)^{\frac{-1}{\phi_y}} \left(\frac{K^y}{N^y} \right)^{\alpha_y} (1 - \alpha_y)$$

$$R^y = A^y \left[\left((K^y)^{\alpha_y} (N^y)^{1-\alpha_y} \right)^{\frac{\phi_y - 1}{\phi_y}} + (E^y)^{\frac{\phi_y - 1}{\phi_y}} \right]^{\frac{1}{\phi_y - 1}} \left((K^y)^{\alpha_y} (N^y)^{1-\alpha_y} \right)^{\frac{-1}{\phi_y}} \left(\frac{N^y}{K^y} \right)^{1-\alpha_y} \alpha_y$$

4. The representative clean energy firm's demands for K^c and N^c satisfy:

$$w = p^c A^c (K^c)^{\alpha_e} (N^c)^{-\alpha_e} (1 - \alpha_e) \tag{12}$$

$$R^c = p^c A^c (K^c)^{\alpha_e - 1} (N^c)^{1-\alpha_c} \alpha_e \tag{13}$$

5. The representative dirty energy firm's demands for K^d and N^d satisfy:

$$w = p^d A^d (K^d)^{\alpha_e} (N^d)^{-\alpha_e} (1 - \alpha_e) \tag{14}$$

$$R^d = p^d A^d (K^d)^{\alpha_e - 1} (N^d)^{1-\alpha_e} \alpha_e \tag{15}$$

6. The Social Security tax satisfies:

$$\tau^s = \frac{S \sum_{j \geq j^r} \Phi(x)}{wN} \tag{16}$$

7. Transfers from accidental bequests satisfy:

$$T^a = (1 - \Psi) a' \Phi(x) \tag{17}$$

8. The government budget balances:

$$
\begin{aligned}
G = \tau^d E^d - T^d + \\
\sum \left[\tau^k r(a+T^a) + T^n\big(\mu h w(1-.5\tau^s)\big) + T^s(S, y^k)\right] \Phi(x)
\end{aligned}
\tag{18}
$$

9. Markets clear:

$$
N^c + N^d + N^y = \sum \varepsilon h \Phi(x) \tag{19}
$$

$$
K^q_{demand} = K^q_{supply} \quad \text{for} \quad q \epsilon \{y, c, d\} \tag{20}
$$

$$
E^q_{demand} = E^q_{supply} \quad \text{for} \quad q \epsilon \{c, d\} \tag{21}
$$

10. The aggregate resource constraint holds:

$$
\begin{aligned}
\sum (c + a')\Phi(x) + G + \lambda \sum_{q \epsilon \{c,d,y\}} |I^q| \mathbb{1}_{I^q < 0} \\
= Y + (1-\delta)(K^c + K^d + K^y)
\end{aligned}
\tag{22}
$$

11. 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.

2.7 Stochastic Stationary Equilibrium

In the stochastic stationary equilibrium, households expect that the government will introduce a carbon tax next period with probability ρ. Once the government implements the carbon-tax policy, the economy sets on a deterministic transition path to a deterministic equilibrium without any risk of another policy shock. Households internalize this policy uncertainty into their consumption and savings decisions. Let indicator variable $z = 1$ denote the introduction of the carbon tax; zero otherwise. The household's optimization problem in the stochastic stationary equilibrium with no existing carbon tax, $z = 0$, is,

$$\begin{aligned} V(a'_{ij}; j, z=0) = \max_{a'_{ij}, h_{ij}, c_{ij}} \; & u(c_{ij}, h_{ij}) \\ & + \beta \Psi_j \left[\rho V(a'_{ij}; j+1, z'=1) + (1-\rho) V(a'_{ij}; j+1, z'=0) \right], \end{aligned} \tag{23}$$

subject to the budget and non-negativity constraints in equations (8) - (10). Equation (23) is identical to value function in the deterministic equilibrium (equation (7)) except that the continuation value is a weighted average of the continuation value when the policy is not introduced the next period, $V(\cdot\ ; z = 0)$, and the continuation value when the policy is introduced the next period, $V(\cdot\ ; z = 1)$. The continuation value when the policy is introduced is the value function along the deterministic transition path to a deterministic equilibrium with the carbon tax policy is place.

The definition of a stochastic stationary stationary equilibrium is the same as for the deterministic equilibrium except for optimization problems for the household and capital intermediary. The households optimize the stochastic value function (equation (23)) instead of the deterministic value function (equation (7)). The capital intermediary chooses the allocation of next period's capital to maximize the *expected* rate of return,

$$E(r') = \left(\frac{(K^y)'}{K'} \right) E((r^y)') + \left(\frac{(K^c)'}{K'} \right) E((r^c)') \left(\frac{(K^d)'}{K'} \right) E((r^d)'). \tag{24}$$

The expectation is taken over the probability, ρ, that the government introduces the carbon-tax policy.

3 Discussion

The capital intermediary chooses next period's levels of clean, dirty, and non-energy capital to maximize the expected average rate of return. In the deterministic equilibrium, this optimization yields the standard result that the rates of return are equated across sectors,

$$r^c = r^d = r^y. \tag{25}$$

In the stochastic equilibrium, the intermediary equates the *expected* rates of return across sectors,

$$E(r^c) = E(r^d) = E(r^y). \tag{26}$$

The primary direct effect of the carbon tax is on the returns to clean and dirty capital. We focus our discussion on understanding these rates of return. Writing out the expectation in equation (26) for clean and dirty capital yields,

$$\rho r^c(z = 1) + (1 - \rho)r^c(z = 0) = \rho r^d(z = 1) + (1 - \rho)r^d(z = 0). \tag{27}$$

The policy uncertainty generates an upside risk for clean capital, $r^c(z = 1) > r^c(z = 0)$, relative to the deterministic equilibrium. The tax increases demand for clean energy, raising its relative price. All else constant, the increase in price raises the marginal product of clean capital and the corresponding rate of return.

In contrast, the policy uncertainty generates a downside risk for dirty capital, $r^d(z = 1) < r^d(z = 0)$, relative to the deterministic equilibrium. The tax reduces demand for dirty energy, lowering its relative (before tax) price. All else constant, the decrease in price lowers the marginal product of dirty capital and the corresponding rate of return. The rate of return to dirty capital falls even further if the introduction of the policy leads to aggregate disinvestment in dirty capital, causing the intermediary to incur the scrapping cost.

We combine the effects for clean and dirty capital to understand how the policy uncertainty affects the average return to capital and thus the aggregate level of investment in the economy. Start with the equilibrium allocation of capital from the deterministic equilibrium that equates the rate of return across all three sectors. All else constant, the upside risk to clean capital raises the average expected rate of return while the downside risk to dirty capital reduces the average expected rate of return. The downside risk to dirty capital dominates for two reasons. First, in the empirically, relevant region of the parameter space, dirty capital is a larger share of the total capital stock than clean capital. Thus, the decrease in the return to dirty affects a larger portion of the total capital stock than the increase in the return to clean, reducing the expected average rate of return. Second, the policy will likely cause the intermediary to scrap a portion of the dirty capital. This scrapping cost implies that the reduction in the return to dirty capital is likely to be much larger than the increase in the return to clean capital.

To summarize, the policy uncertainty has two primary effects on macroeconomic aggregates. First, it leads to a higher ratio of clean to dirty capital, shifting the economy towards cleaner energy production. Second, it reduces the return to saving. The lower return to saving implies that agents accumulate less capital, which, in turn, reduces output relative to the deterministic equilibrium. Both of these effects imply that carbon emissions will be lower in the stochastic equilibrium than in the deterministic equilibrium.

4 Calibration

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.

Table 1: Calibration Parameters (Baseline)

Parameter	Value	Source
Demographics		
Retire Age: j^r	66	Assumption
Max Age: J	100	Assumption
Survival probability : Ψ_j	Bell and Miller (2002)	Data
Population growth: n	1.1%	Data
Age-specific productivity: $\{\varepsilon_j\}_{j=20}^{j^r-1}$		Kaplan (2012)
Firm Parameters		
Capital share final good: α_y	0.36	Data
Capital share energy: α_e	0.81	Data
Clean energy productivity: A^c	71	Method of moments
Dirty energy productivity: A^d	177.5	Method of moments
Productivity: A^y	1	Normalization
Scrapping cost: λ	0.5	Ramey and Shapiro (1999)
Final good substitution elasticity: ϕ_y	0.5	Van der Werf (2008)
Energy substitution elasticity: ϕ_e	2.5	Papageorgiou et al. (2017)
Depreciation: δ	0.083	Method of moments
Preference Parameters		
Conditional discount: β	1.00025	Method of moments
Risk aversion: θ_1	2	Conesa et al. (2009)
Frisch elasticity: θ_2	0.5	Kaplan (2012)
Disutility of Labor: χ	62.5	Method of moments
Government Parameters		
Labor tax function: Υ_0	0.258	Gouveia and Strauss (1994)
Labor tax function: Υ_1	0.71	Gouveia and Strauss (1994)
Labor tax function: Υ_2	1.75	Clears market
Capital tax rate: τ^k	0.36	Trabandt and Uhlig (2011)
Government spending: G	0.12	Method of moments

4.1 Demographics

Agents enter the model at age 20 and are exogenously forced to retire at age $j^r = 66$. If an individual survives until 100, she dies the next period. We choose the conditional survival probabilities based on the estimates in Bell and Miller (2002). We adjust the size of each cohort's share of the population to be consistent with a population growth rate of 1.1 percent. We set $\{\epsilon_j\}_{j=20}^{j^r-1}$ to match the average hourly earnings estimated in Kaplan (2012).

4.2 Preferences

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.[5] We choose γ so that energy share of household expenditures is 10.2 percent (Fried et al. 2018).

4.3 Production

We use 0.5 for the elasticity of substitution between the capital-labor composite and energy, ϕ_y in the production technology for the final good. This parameter choice is within the range of estimates reported in Van der Werf (2008). We use $\alpha_y = 0.36$ for capital's share in the capital-labor composite. Papageorgiou et al. (2017) use sectoral data from the Word Input-Output Database across 26 to estimate the elasticity of substitution between clean and dirty inputs. Their estimates range from 2-3, depending on the sector. Based on their evidence, we set the elasticity of substitution between clean and dirty energy inputs, $\phi_e = 2.5$.

We calibrate labor share in clean and dirty energy production, $1-\alpha_e$, as the cost share of labor in value added in the fossil energy sector.[6] Fossil energy corresponds to coal, oil, and natural gas extraction, as well as to the production of petroleum and coal products (such as gasoline). We map fossil energy to the mining and petroleum and coal products industries (NAICS codes 21 and 324) in the BEA accounts. The average labor share over the past previous decade (2006-2016) in these two industries combined is is 0.19.[7]

We choose the clean and dirty energy productivity parameters, A^c and A^d, to match two macro-energy moments: (1) energy's share of GDP, and (2) dirty energy as a fraction of

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

[6] To our knowledge, similar data is not available for the clean energy sector.

[7] Data downloaded on 4/18/2018 from https://www.bea.gov/industry/gdpbyind_data.htm.

total energy. Following Golosov et. al (2014), we target energy's share of GDP equal 0.04,

$$\frac{p^c E^c + p^d E^d}{Y} = 0.04. \tag{28}$$

All else constant, a symetric change in the energy productivity parameters affects the relative price of energy, which, in turn, affects its share of aggregate production.

The ratio of energy productivities, A^d/A^c, determines the fraction of total energy use that is dirty. For example, if dirty energy productivity is larger than clean energy productivity, $A^d/A^c > 1$, then the relative price of dirty energy is less than that of clean energy, implying that agents will use more dirty energy. We target this ratio of energy productivities to match the fraction of US primary energy consumption from fossil fuel in 2017, 0.8.[8]

Following Ramey and Shapiro (1998), we set the value of the scrapping cost, λ equal to 0.5. This choice implies that capital looses half of its value if it switches sectors. We determine the depreciation rate, δ, so that investment equals 25.5 percent of aggregate output.

4.4 Government Policies and Tax Functions

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

$$T^h(\tilde{y}^n_{i,j,t}; \Upsilon_0, \Upsilon_1, \Upsilon_2) = \Upsilon_0 \left(\tilde{y}^n_{i,j,t} - \left((\tilde{y}^n_{i,j,t})^{-\Upsilon_1} + \Upsilon_2 \right)^{\frac{-1}{\Upsilon_1}} \right). \tag{29}$$

Parameter Υ_0 governs the average tax rate and parameter Υ_1 controls the progressivity of

[8] Data on primary energy consumption by source are from EIA Table 1.3. In the model, clean and dirty energy do not necessarily have the same units. Therefore, we multiply the quantity of each type of energy by its relative price and target $p^d E^d/(p^c E^c + p^d E^d) = 0.8$. This target is equivalent to the empirical ratio of fossil primary energy consumption to total primary energy consumption if the empirical prices of clean and dirty energy are the same on the margin. For example, the retail price of electricity is independent of whether the electricity is produced with coal or with solar.

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.[9]

We determine government consumption, G, so that it equals 15.5 percent of output, the average value in the U.S data.[10] We set the tax rate on capital income, τ^k, to 36 percent based on estimates in Kaplan (2012), Nakajima (2010) and Trabandt and Uhlig (2011). To determine the size of the Social Security payments in the baseline steady state, we follow Conesa and Krueger (2006) and assume that retired agents receive 50 percent of the average income of all working individuals

$$S = 0.5 \left(\frac{wN}{\sum_{j<j^r} \Phi(x)} \right). \tag{30}$$

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

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

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

Social Security payments each year to ensure that the purchasing power remains constant. Consistent with this policy, we adjust the Social Security payment in each simulation to ensure that the retiree can buy the same bundle of energy and non-energy goods as she could in the baseline steady state.[11] We choose the payroll tax, τ_t^s, to ensure that the Social Security system has a balanced budget in every period.

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

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

Table 2: Model Fit

Moment	Target	Model
Household energy budget share	0.102	0.102
Hours	0.333	0.333
Govt spending to GDP	0.155	0.155
Capital to GDP	2.7	2.70
Investment to GDP	0.255	0.255
Fraction of dirty energy	0.8	0.80
Energy share of GDP	0.04	0.04

5 Computational Experiment

We analyze the effects of policy uncertainty surrounding the introduction of a 35 dollar per ton carbon tax with all revenues returned to the household through equal lump-sum

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

transfers. We calculate three stationary equilibria: (1) a deterministic (*initial*) equilibrium without the carbon tax policy, (2) a deterministic (*final*) equilibrium with the carbon tax policy, and (3) a stochastic equilibrium, in which the there is no carbon tax policy in place but there is a five percent probability each period that the government introduces the carbon tax policy.

The value function for the stochastic equilibrium is given in equation (23) with probability $\rho = 0.05$. To solve for the stochastic equilibrium, we iterate on two guesses: (1) the stochastic equilibrium itself and (2) the transition path from the initial equilibrium to final equilibrium with the policy in place. To update each guess, we simulate the economy over a 100 year period in which agents internalize a 5 percent probability that the tax will be implemented. The tax is not implemented until period 101, after which the economy transitions to the final equilibrium. All uncertainty is resolved in period 101; the transition path and the final equilibrium are deterministic.[12] We use the last period prior to the introduction of the tax, period 100, as our updated guess for the stochastic steady state. See Peterman and Sommer (Forthcoming) for a detailed description of how to solve for a stochastic equilibrium.

6 Preliminary results

Table 3 reports the aggregate values of the variables in the initial, stochastic, and final equilibria. Figures 1-2 plot the values of different aggregates. In all three figures, the red cross plots the value of the variable in the initial equilibrium, the black dot plots its value in the stochastic equilibrium, and the line shows the evolution of the variable along the deterministic transition from the stochastic to the final equilibrium. The carbon tax is introduced in period 1.

[12] We find that the stochastic economy is stationary after well before year 100.

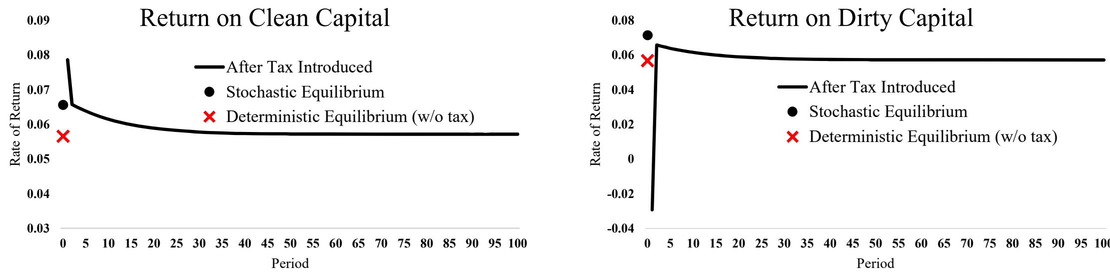
Table 3: Effects of Policy Uncertainty on Macro-Aggregates

	Deterministic. Eq. w.o. tax **Initial**	Stochastic. Eq. w.o. tax **Stochastic**	Deterministic. Eq. with tax **Final**
	(1)	(2)	(3)
Wage: w	0.96	0.92	0.94
Dirty return: r^d	0.057	0.066	0.057
Clean return: r^c	0.057	0.071	0.057
Non-energy return: r^y	0.057	0.066	0.057
Clean/Dirty capital: K^c/K^d	0.253	0.275	0.519
Total capital: K	2.07	1.86	2.01
Dirty energy: E^d	13.2	12.1	9.82
Clean energy: E^c	1.34	1.32	2.04
Efficiency labor: N	0.5	0.5	0.5
Output: Y	0.77	0.74	0.76
Carbon intensity: E^d/Y	17.22	16.4	12.99

The anticipation of the carbon tax policy has substantial effects on macro-aggregates. Comparing the stochastic and initial equilibria (Columns (1) and (2) of Table 3) reveals that the policy expectations shift the economy towards cleaner energy production. The ratio of clean to dirty capital, K^c/K^d, increases by 8.7 percent, from 0.253 in the initial equilibrium to 0.275 in the stochastic equilibrium.

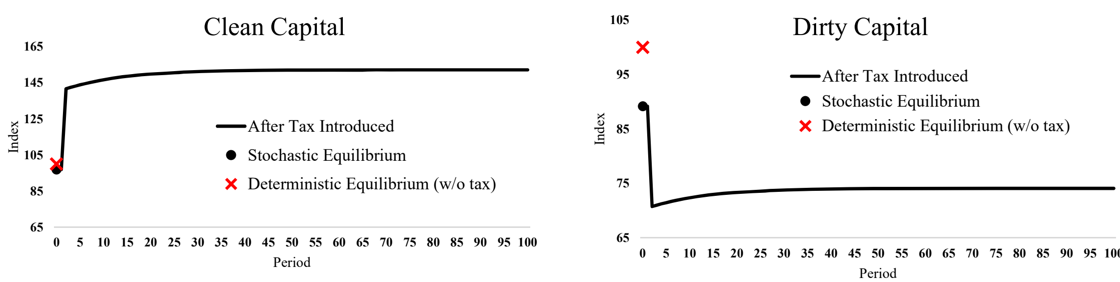
As discussed in Section 3, the intuition for this relative increase in clean capital hinges on how the policy uncertainty affects expected rates of return to clean and dirty capital. The left and right panels of Figure 1 plots the rates of return to clean and dirty capital, respectively. The policy uncertainty creates an upside risk for clean capital and a downside risk for dirty capital. In period 1, the period the carbon tax is introduced, the rate of return to clean capital increases from 0.065 in the stochastic equilibrium to 0.079. Likewise, the rate of return to dirty capital decreases from 0.071 to -0.029.

Figure 1: Rates of Return to Clean and Dirty Capital



The rate of return to dirty capital in period one falls by more than the rate of return to clean capital rises. This is because a portion of the dirty capital is scrapped. Figure 2 plots the levels of clean and dirty capital. The introduction of the carbon tax policy (period 1) leads to an immediate drop in dirty capital and an immediate increase in clean capital. The intermediary must pay this scrapping cost on the dirty capital, generating a negative rate of return.

Figure 2: Levels of Clean and Dirty Capital



In the stochastic equilibrium (period 0), the expected rates of return across all types of capital are equal. However, the upside to risk to clean capital if the government introduces the policy (period 1) reduces the realized rate of return to clean capital in the stochastic equilibrium. Similarly, the downside risk to dirty capital raises the realized rate of return in the stochastic equilibrium. All uncertainty is resolved in period 1. After period 1, the capital stocks adjust so that the rates of return are equal on the transition path to the final equilibrium.

The increase in the ratio of clean to dirty capital reduces the carbon intensity of output by 4.8 percent. However, this reduction in carbon intensity comes at a substantial cost. Total capital in the stochastic equilibrium is ten percent lower than in the initial equilibrium. The decrease in capital reduces output by 3.9 percent, from 0.77 in the initial to 0.74 in the stochastic. As discussed in Section 3, output falls because the policy uncertainty reduces the return to saving at a given level of the capital stock. Both the fall in output and the shift towards cleaner energy production reduce total carbon emissions. Carbon emissions in the stochastic equilibrium are 8.3 percent lower than in the initial equilibrium.

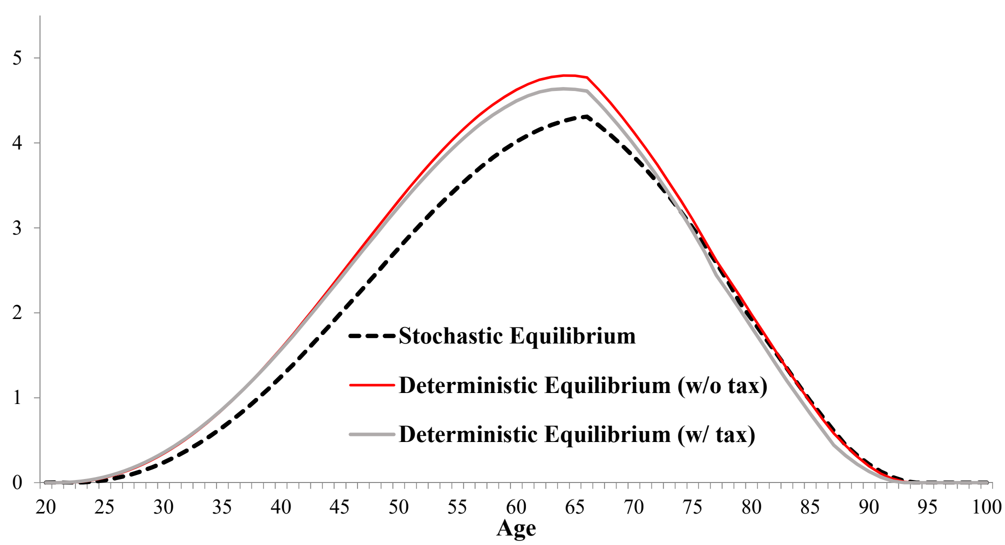
Most previous literature abstracts from the effects of anticipation when they evaluate carbon tax policy. Implicitly, these papers compare the initial and final equilibrium (Columns (1) and (3) of Table 3). However, if the world is more accurately represented by the stochastic equilibrium (Column (2) of Table 3), then such a comparison could misrepresent the true effects of introducing a carbon tax. For example, comparing Columns (1) and (3) implies that the introduction of the carbon tax reduces emissions by 25.6 percent, from 13.2 in the initial to 9.82 in the final. However, if instead we compare the stochastic and final equilibria (Columns (2) and (3)), then we find that the *introduction* of the policy only reduces emissions by 18.8 percent. Over one quarter of the emissions reduction occurs simply because agents expect the government to introduce the policy in the future.

Comparing the initial and final equilibria, implies that the introduction of the carbon tax policy is costly; output falls from 0.77 in the initial to 0.76 in the final. However, if instead agents expect the government to implement the policy (Column (2) of Table 3), then the actual introduction of the policy causes output to *rise*, from 0.74 to 0.76. Thus introduction of the carbon tax policy leads to an increase in production instead of a decrease in production if agents anticipate the policy.

Output is higher in the final equilibrium than in the stochastic equilibrium for two reasons. First, a large portion of the dirty capital is scrapped when the government introduces the policy. Dirty capital falls immediately after the introduction of the policy (see Figure 2). As a result, agents must pay the corresponding scrapping cost, reducing the average return to savings. In contrast, there is no uncertainty in the final equilibrium, and thus capital is not scrapped or expected to be scrapped in the future. All else constant, this difference implies that the rate of return to saving is higher in the final equilibrium than in the stochastic equilibrium, leading to higher capital and output.

The second reason that output is higher in the final equilibrium is that the policy uncertainty shifts the savings profile over the life cycle to the right. Figure 3 plots total savings at each age in the stochastic equilibrium (dashed line), initial equilibrium (red line) and final equilibrium (gray line). Comparing the profiles in the stochastic and final equilibria, we see that older agents save more in the stochastic equilibrium while younger agents save less. Since the economy has more young agents than old agents, the reduction in saving by the young dominates the increase in saving by the old, further reducing the total capital stock in the stochastic equilibria.

Figure 3: Savings Profile



We use the consumption equivalent variation (CEV) to calculate the welfare implications of the policy uncertainty. We define the $\text{CEV}_{a,b}$ as the expected percent increase in consumption the agent would need in every period in equilibrium a such that they are indifferent between living in equilibrium a and living in equilibrium b. A positive CEV implies that the agent is better off in equilibria b while a negative CEV implies that the agent is better off in equilibria a.

Table 4: Consumption Equivalent Variation (percent)

$\text{CEV}_{1,2}$	$\text{CEV}_{1,3}$	$\text{CEV}_{2,3}$
-4.71	-0.67	4.28

Table 4 reports the CEV between three different pairs of equilibria. To calculate the welfare cost of the policy uncertainty, we calculate the CEV between the initial and stochastic equilibria, $\text{CEV}_{1,2}$ (first Column of Table 4). $\text{CEV}_{1,2}$ equals -4.71 percent, implying a substantial cost to policy uncertainty. These costs primarily result from the drop in the capital stock and corresponding fall in output.

We compare the long-run welfare cost of the policy if agents do not anticipate the carbon tax, $\text{CEV}_{1,3}$ with the long-run welfare cost if agents do anticipate the tax, $\text{CEV}_{2,3}$. $\text{CEV}_{1,3}$ equals -4.71 percent, implying a large welfare cost. However, if instead agents do anticipate the policy, than the introduction of the carbon tax policy generates long-run non-environmental welfare benefits. $\text{CEV}_{2,3}$ is positive and equal to 4.28 percent. Again, the welfare effects are primarily driven by the changes in the aggregate capital stock and the corresponding changes in output.

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