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Climate Policy and the Long-Run Interest Rate: Insights from a Simple Growth Model

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Abstract

We study the impact of climate policy on the long-run real interest rate in a tractable climate-economy model based on the work of Golosov et al. (2014). When the growth rate of the carbon tax exceeds the growth rate of the price of at least one type of fossil energy, the tax reduces the long-run growth rates of consumption and investment, pushing the interest rate up. We find that if fossil energy prices are constant, a carbon tax that grows at 3.5 percent per year decreases the long-run interest by over 50 basis points. This carbon tax growth rate achieves net zero emissions at the lowest possible cost.

Keywords Climate Policy, R-star

JEL Classification Codes H23, O44, Q43, Q54

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1 Introduction

Long-run real interest rates in the U.S. and around the world have generally declined over the past 40 years.[1,2] As Summers and Rachel (2019) highlights, research has pointed to a number of potential contributors to the decline including demographic trends (Gagnon et al., 2021; Carvalho et al., 2016; Lisack et al., 2021; Eggertsson et al., 2019), income inequality (Auclert and Rognlie, 2018; Straub, 2019), and supply-side forces such as investment-specific technical change, intangible capital and market power (Eichengreen, 2015; Farhi and Gourio, 2018). Going forward, policies designed to transition the economy to clean energy, such as a carbon price or a clean energy subsidy, could lead to new shifts in the long-run interest rate. This paper develops a simple growth model to show how these policy instruments could affect long-run consumption and investment growth, and thus impact the long-run interest rate.

Our model follows Golosov et al. (2014) and extends the neoclassical growth framework to include different types of energy.[3] Output is produced from capital, labor, and energy services. Energy services are a composite of clean energy and three types of fossil energy: coal, oil, and natural gas. We define the long-run interest rate as the interest rate on an asymptotic balanced growth path. As is standard in growth theory, all prices, including the interest rate, are real and are denominated in terms of the numeraire. The long-run interest rate depends on the growth rate of total factor productivity (TFP), which in turn depends on the growth rates of the fossil fuel and clean energy prices, and on climate policy. We parameterize the model using data from the EIA on energy prices, consumption, and carbon emissions. We consider two types of climate policy; a tax per unit of carbon energy and a subsidy per unit of clean energy.

We first study the effect of an exogenous carbon tax on the long-run interest rate. A carbon tax will increase the growth rate of the price of energy services if the tax grows faster than the price of at least one type of fossil fuel. In this case, the carbon tax reduces TFP growth, pushing down the long-run interest rate. A carbon tax that grows at 2 percent per year, consistent with the optimal policy in Golosov et al. (2014), reduces the long-run interest rate by only 1 basis point if fossil fuel prices grow at their historical rates in the long

[1] There is debate if this decline continued, halted, or reversed following the pandemic.

[2] A similar pattern exists short-run real interest rates in the U.S. since 1980 (Aladangady et al., 2021))

[3] We make three small deviations from Golosov et al. (2014). First, we consider oil and natural gas as separate sources of energy. The second two deviations allow us to obtain analytical solutions. We set the elasticity of substitution between energy sources to be 1 instead of 0.95 and we abstract from climate damages.

run, but by 30 basis points if fossil fuel prices are constant in the long run.

We next consider the effect of a carbon tax that achieves net zero emissions. Net zero requires cumulative emissions to remain below a predetermined level, which we call the carbon budget. Using the standard Hotelling (1931) logic, we show that staying within a given carbon budget requires an ever-rising carbon tax. As before, the impact of this carbon tax on the long-run interest rate depends on the growth rate of fossil-energy prices. For example, attaining net zero reduces the long-run interest rate by 8 basis points if fossil-energy prices grow at their historical rates, but by 54 basis points if fossil-energy prices are constant. Interestingly, the effect of the carbon tax on the long-run interest rate does not depend on the temperature target, or equivalently, the size of the carbon budget. The size of the carbon budget would affect the initial level of the carbon tax, but the long-run interest rate depends on the growth rate of the tax, not the level.

Growing carbon prices are not only a theoretical tool to achieve net zero, they are also a common feature of many climate policies and policy proposals. For example, the Clean Competition Act, a current bill before the U.S. congress, would impose a carbon tax on carbon-intensive manufacturing firms that grows at five percent per year after inflation. Additionally, the cap on emissions in a cap-and-trade system is typically designed to ratchet down over time, pushing the implied price on carbon up. For example, the cap in the EU-ETS, the world's largest cap-and-trade system, was reduced by 2.2 percent each year from 2021-2023 and is scheduled to fall by over 4 percent each year between 2024 and 2030. These decreases in the cap are projected to lead to substantial increases in the carbon price (Pahle et al., 2022).

Our results imply that attaining net zero could reduce the long-run interest rate between 8 and 54 basis points for plausible assumptions about fossil-energy price growth. It is useful to put these implications in context. The long-run interest rate has fallen by approximately 300 basis points over the past 40 years (Summers and Rachel, 2019). An additional decrease of 50 basis points would constitute 15 percent of the large historical decline. In the monetary policy setting, a 50 basis point fall in the long-run neutral rate is equivalent to two standard size rate cuts. Moreover, changes in long-run real interest rates affects the relative return to investing in renewables and fossil fuels, since the former tend to be more capital-intensive (Schmidt et al., 2019; Calcaterra et al., 2024).

Another common policy approach to the clean transition is to implement a subsidy for clean energy. For example, the Inflation Reduction Act in the U.S. includes subsides for wind and solar electricity generation (Bistline et al., forthcoming). We extend the model to look at the effect of a subsidy per unit of clean energy on the long-run interest rate. Similar to a carbon tax, we show that the clean-energy subsidy will only affect the long-run interest rate if the growth rate of the subsidy exceeds the growth rate of the price of clean energy. In this case, the clean-energy subsidy reduces the growth rate of the price of energy services, raising TFP growth and increasing the long-run interest rate.

Our paper is part of a small, but growing literature on climate policy and interest rates. Mongelli et al. (2022) provides an overview of the different channels through which climate change could affect the natural rate of interest. Fries (2023) and Mehrotra (2024) study the impact of climate policy on the short-run real interest rate in models without growth. Our work complements these earlier studies by adding growth and studying on the long-run implications of climate policy. Focusing on an alternative channel, Benmir et al. (2020) show that a pro-cyclical carbon tax can reduce aggregate volatility (from non-climate shocks), which decreases precautionary savings, putting upward pressure on interest rates.

2 Main Analysis: Effect of a Carbon Tax

We study a simple neoclassical growth model in which gross output is produced from capital, labor, and energy services. Energy services are a composite of clean energy and three types of fossil energy: coal, natural gas, and oil. The carbon tax raises the price per unit of carbon energy from each type of fossil energy. We solve the model for the asymptotic balanced growth path. We define the long-run interest rate, r^*, as the interest rate on the asymptotic balanced growth path. We analyze the effect of the carbon tax on the long-run interest rate.

2.1 Model Structure

Time is discrete and infinite: $t = 0, 1, 2 \ldots$.[4] The economy is inhabited by a unit measure of identical households. Households have preferences over consumption according to the period utility function:

$$U(C_t) = \frac{C^{1-\sigma}}{1-\sigma}.$$

Households supply labor in-elastically to firms and save through the accumulation of physical capital. We normalize the labor supply to unity.

[4]When we quantify the model, we consider annual time steps, so that all interest rates and growth rates are per year.

A representative, perfectly competitive firm produces gross output (Q_t) from capital (K_t), labor (L_t), and energy services (E_t) using a Cobb-Douglas production technology:

$$Q_t = K_t^{\alpha} E_t^{\nu} (A_t L_t)^{1-\alpha-\nu}. \tag{1}$$

Technology term, A_t, grows at rate g_A. The Cobb-Douglas functional form implies that there is a unitary elasticity of substitution between energy and capital or labor. Hassler et al. (2021) show that while a unitary elasticity of substitution might be too high in the short run, it matches the aggregate data reasonably well in the long run, the focus of our analysis. Gross output is the numeraire and we measure all prices relative to the price of gross output.

Energy services are produced from clean energy, indexed by $i = 0$, and three types of fossil energy indexed by $i = 1, 2, 3$, according to the Cobb-Douglas production function:

$$E_t = \bar{E} \prod_{i=0}^{3} (E_t^i)^{\gamma_i}, \tag{2}$$

where $\gamma_i \in (0, 1)\ \forall i$ and $\sum_{i=0}^{3} \gamma_i = 1$. Following Golosov et al. (2014), we measure fossil energy in units of carbon emissions; one unit of any type of fossil energy in our model generates one unit of emissions. The technology term $\bar{E}$ aggregates across the units of clean and fossil energy to determine the overall units for energy services.

The production function for energy services imposes a unitary elasticity of substitution between fossil and clean energy. The appropriate value of this elasticity of substitution has been the subject of much debate in the environmental literature. Some analyses argue for values at or below one (see e.g., Stern, 2012; Golosov et al., 2014) while others argue for values closer to two or three (see e.g., Acemoglu et al., 2012; Papageorgiou et al., 2017). The unitary elasticity of substitution is within the range of values considered by earlier work and, importantly for our context, allows the model to have a balanced growth path with a well-defined interest rate.

Clean energy and each type of fossil energy are produced from units of final good with marginal cost, p_t^i. Production is perfectly competitive. In equilibrium, the price of each type of energy equals its marginal cost. The marginal cost, and hence the price, of energy type i grows at rate g_p^i. We order the fossil energy types based on the growth rate of their prices, such that $0 \leq g_{p^1} \leq g_{p^2} \leq g_{p^3}$. The government can impose per-unit tax on carbon emissions, $\tau_t > 0$, which raises the price of fossil energy type i from p_t^i to $p_t^i + \tau_t$. The tax grows at rate g_τ. The government returns all tax revenue back to households through lump-sum transfers.

Final output (Y_t) available for consumption and investment is given by

$$Y_t = Q_t - \sum_{i=0}^{3} p_t^i E_t^i. \tag{3}$$

Capital accumulates according to the standard law of motion,

$$K_{t+1} = Y_t - C_t + (1-\delta)K_t, \tag{4}$$

where $\delta \in (0,1)$ is the depreciation rate and C_t is consumption.

The representative household chooses consumption and investment to maximize the present discounted value of lifetime utility,

$$\max_{C_t, K_{t+1}} \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\sigma}}{1-\sigma} \tag{5}$$

subject to the budget constraint

$$C_t + K_{t+1} = (1 + R_t - \delta)K_t + w_t L_t + T_t, \tag{6}$$

where T_t is rebated tax revenue, w_t is the market wage, R_t is the rental rate on capital, and β denotes the discount factor. The interest rate equals

$$r_t \equiv R_t - \delta. \tag{7}$$

2.2 Decentralized Equilibrium

Our outcome of interest is the long-run interest rate. In equilibrium, the interest rate is entirely determined by the growth rate of consumption. The first order conditions from the household's optimization problem yield the standard consumption-Euler equation,

$$C_t^{-\sigma} = \beta(1 + r_{t+1})C_{t+1}^{-\sigma}. \tag{8}$$

Re-arranging the Euler equation to solve for the interest rate yields

$$r_{t+1} = \frac{(1 + g_{Ct})^{\sigma}}{\beta} - 1, \tag{9}$$

where $g_{Ct} \equiv C_{t+1}/C_t - 1$ is the growth rate of consumption.

In the long run, the growth rate of consumption is entirely determined by the growth rate of total factor productivity (TFP), as in the standard neoclassical growth model. Thus, any impact of a carbon tax on the long-run value of the real interest rate, r^*, will stem from the effect of the carbon tax on the long-run growth rate of TFP. We next derive the expression for TFP in our model.

To determine TFP, we calculate the value-added production function, equal to the production function for gross output (equation (1)) minus the optimized values of the intermediate energy inputs. Profit maximization for the representative producer of energy services yields the following relative demands for each type of energy:

$$p_t^i + \tau_t = \gamma_i p_t^E \left(\frac{E_t}{E_t^i} \right), \quad i = 1, 2, 3; \quad p_t^0 = \gamma_0 p_t^E \left(\frac{E_t}{E_t^0} \right), \tag{10}$$

and the price index for energy services

$$p_t^E = \tilde{\gamma} (p_t^0)^{\gamma_0} \prod_{i=1}^{3} (p_t^i + \tau_t)^{\gamma_i}. \tag{11}$$

Variable $\tilde{\gamma} = \prod_{i=0}^{3} \gamma_i^{-\gamma_i}$ is a constant. We use g_{p^E} to denote the growth rate of the price of energy services. The zero-profit condition for the energy-services producer implies that

$$p_t^E E_t = p_t^0 E_t^0 + \sum_{i=1}^{3} (p_t^i + \tau_t) E_t^i. \tag{12}$$

Profit maximization for the final good producer yields the relative demand for energy services and capital,

$$p_{E,t} = \nu K_t^{\alpha} E_t^{\nu - 1} \left(A_t L_t \right)^{1-\alpha-\nu}, \tag{13}$$

$$R_t = \alpha K_t^{\alpha-1} E_t^{\nu} \left(A_t L_t \right)^{1-\alpha-\nu}. \tag{14}$$

Combining, (13) with (1), (3), (11), and (12) yields the value-added production function,

$$Y_t = \left(1 - \nu \left(\gamma_0 + \sum_{i=1}^{3} \gamma_i \frac{p_t^i}{\tau_t + p_t^i} \right) \right) \nu^{\frac{\nu}{1-\nu}} \left(p_t^E \right)^{\frac{-\nu}{1-\nu}} K_t^{\tilde{\alpha}} \left(A_t L_t \right)^{1-\tilde{\alpha}}. \tag{15}$$

Constant $\tilde{\alpha} \equiv \frac{\alpha}{1-\nu}$ is the share of value-added paid to capital.

Total factor productivity, $TFP_t \equiv \frac{Y_t}{K_t^{\tilde{\alpha}} L_t^{1-\tilde{\alpha}}}$, is given by

$$TFP_t = \underbrace{A_t^{1-\tilde{\alpha}}}_{\text{Technology}} \times \underbrace{\nu^{\frac{\nu}{1-\nu}} \left(p_t^E\right)^{\frac{-\nu}{1-\nu}}}_{\text{Energy Prices}} \times \underbrace{\left(1 - \nu \left(\gamma_0 + \sum_{i=1}^{3} \gamma_i \frac{p_t^i}{\tau_t + p_t^i}\right)\right)}_{\text{Rebating} \to \text{constant}}. \tag{16}$$

We break the expression for TFP into three components. The first term is the standard productivity term from the neoclassical growth model, which we label as technology. The second term captures the effect of the price of energy services on productivity. Energy services affect productivity with elasticity $-\nu/(1-\nu) < 0$. Intuitively, when energy services are more expensive, firms use less energy, and as a result, they produce less output from a given quantity of capital and labor. The magnitude of this elasticity is decreasing in ν. Thus, the effect of any change in the price of energy services on TFP is limited by the relatively small factor share of energy in gross output.

The last term is a nuisance term. It is equal to one minus the fraction of gross output paid to real extraction costs. Without a carbon tax, this term collapses to $1 - \nu$ where ν is the energy expenditure share of gross output. With a carbon tax, this term is greater than $1 - \nu$ because a portion of energy expenditures are due to real extraction costs and a portion are due to the tax. In the limit as $t \to \infty$, this term converges to a constant. Therefore, the term has no effect on the long-run growth rate of TFP and we ignore it in the subsequent analysis.

2.3 Balanced Growth

Definition 1. *A* balanced growth path (BGP) *is a path along with C_t and K_t grow at constant rates, g_C^* and g_K^*. We use asterisks $(*)$ to denote BGP values. An* asymptotic balanced growth path *(ABGP) is a BGP that cannot be reached with finite prices and quantities.*

The ABGP is the steady state of the model. Rebating the carbon tax revenue implies that this steady state only occurs in the limit. As is often the case the macro-energy literature, we interpret the ABGP as describing the behavior of the economy at decadal time scales (e.g., Hassler et al., 2021).

Starting with the the value-added production function, we solve for the ABGP using the standard steps. We define the intensive form as

$$z_t = \frac{Z_t}{TFP_t^{\frac{1}{1-\tilde{\alpha}}} L_t}, \quad Z_t \in \{C_t, Y_t, K_t\}.$$

Let $g_{TFP,t}$ be the growth rate of TFP. Then, the dynamics of the economy in intensive form equal:

$$\begin{aligned}
y_t &= k_t^{\tilde{\alpha}}, \\
k_{t+1} &= \frac{y_t - c_t + (1-\delta)k_t}{(1+g_{TFP,t})^{\frac{1}{1-\tilde{\alpha}}}} \\
c_{t+1} &= \left(\frac{\beta(1+r_{t+1})}{(1+g_{TFP,t})^{\frac{\sigma}{1-\tilde{\alpha}}}} c_t^{\sigma} \right)^{\frac{1}{\sigma}} \\
r_t &= \alpha k_t^{\tilde{\alpha}-1} - \delta.
\end{aligned}$$

On the ABGP, g_{TFP}, y_t, k_t, c_t and r_t are constant. The interest rate on the ABGP, r^*, equals:

$$r^* = \beta^{-1}(1+g^*_{TFP})^{\frac{\sigma}{1-\tilde{\alpha}}} - 1, \tag{17}$$

and the remaining variables are given by

$$\begin{aligned}
k^* &= \left(\frac{r^* + \delta}{\tilde{\alpha}} \right)^{\frac{1}{\tilde{\alpha}-1}} \\
y^* &= (k^*)^{\tilde{\alpha}} \\
c^* &= y^* - (1+g^*_{TFP})^{\frac{1}{1-\tilde{\alpha}}} k^* + (1-\delta)k^*.
\end{aligned}$$

2.4 Effect of a Carbon Tax on the Long-Run Interest Rate

Any effect of climate policy on the long-run interest rate must occur though the effect of the policy on the long-run growth rate of TFP. We re-write the expression for the long-run real interest rate in (17) as:

$$\ln(1+r^*) = \frac{\sigma}{1-\tilde{\alpha}} \ln(1+g^*_{TFP}) - \ln(\beta). \tag{18}$$

The growth rate of TFP, in turn, depends on the growth rate of technology and the growth rate of the price of energy services. From (16) we have:

$$\ln(1 + g^*_{TFP}) = (1 - \tilde{\alpha}) \ln(1 + g^*_A) - \frac{\nu}{1 - \nu} \ln(1 + g^*_{P_E}). \tag{19}$$

The growth rate of technology, g^*_A, is exogenous to our model. However, the growth rate of the price of energy services, (11), depends on the growth rate of the price of clean energy and on the growth rates of the tax-inclusive price of each type of fossil energy. On the ABGP, the growth rate of the tax-inclusive fossil-energy prices will either equal the growth rate of the carbon tax or the growth rate of the underlying fossil-energy price, whichever is largest.

We use this intuition to derive the effect of a carbon tax on the long-run interest rate as a function of the growth rates of fossil-energy prices and the growth rate of the tax. First, the growth rate of the price of energy services on the ABGP equals:

$$\ln(1 + g^*_{P_E}) = \begin{cases} \gamma_0 \ln(1 + g_{p^0}) + \sum_{i=1}^{3} \gamma_i \ln(1 + g_{p^i}) & \text{if } g_{p^1} > g_\tau \\ \gamma_0 \ln(1 + g_{p^0}) + \gamma_1 \ln(1 + g_\tau) + \sum_{i=2}^{3} \gamma_i \ln(1 + g_{p^i}) & \text{if } g_{p^2} > g_\tau \geq g_{p^1} \\ \gamma_0 \ln(1 + g_{p^0}) + \sum_{i=1}^{2} \gamma_i \ln(1 + g_\tau) + \gamma_3 \ln(1 + g_{p^i}) & \text{if } g_{p^3} > g_\tau \geq g_{p^2} \\ \gamma_0 \ln(1 + g_{p^0}) + \sum_{i=1}^{3} \gamma_i \ln(1 + g_\tau) & \text{if } g_\tau \geq g_{p^3}. \end{cases} \tag{20}$$

We combine (18), (19) and (20) and apply small value approximations to derive the effect of a marginal change in the growth rate of the carbon tax on the long-run interest rate:

Proposition 1. *On the asymptotic balanced growth path, the marginal effect of a change in the growth rate of a carbon tax on the long-run interest rate equals:*

$$\frac{dr^*}{dg_\tau} \approx \begin{cases} 0 & \text{if } g_{p^1} > g_\tau \\ -\frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times \gamma_1 & \text{if } g_{p^2} > g_\tau \geq g_{p^1} \\ -\frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times (\gamma_1 + \gamma_2) & \text{if } g_{p^3} > g_\tau \geq g_{p^2} \\ -\frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times (\gamma_1 + \gamma_2 + \gamma_3) & \text{if } g_\tau \geq g_{p^3}. \end{cases} \tag{21}$$

The total change in the long-run interest rate between a world with a carbon tax and a world *without equals:*

$$\Delta r^* \approx \begin{cases} 0 & \text{if } g_{p^1} > g_\tau \\ -\frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times \gamma_1 (g_\tau - g_{p^1}) & \text{if } g_{p^2} > g_\tau \geq g_{p^1} \\ -\frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times \sum_{i=1}^{2} \gamma_i (g_\tau - g_{p^i}) & \text{if } g_{p^3} > g_\tau \geq g_{p^2} \\ -\frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times \sum_{i=1}^{3} \gamma_i (g_\tau - g_{p^i}) & \text{if } g_\tau \geq g_{p^3}. \end{cases} \tag{22}$$

Proposition 1 reveals that a carbon tax will only affect the long-run interest rate if it grows faster than the price of the slowest growing type of fossil energy. Optimal climate policy in many climate-economy models includes a gradually rising carbon price (see Golosov et al. (2014), Barrage and Nordhaus (2023), and Acemoglu et al. (2012) for examples). Moreover, the majority of carbon pricing systems around the world feature rising carbon prices.[5] For example, the carbon price in the EU ETS, the world's largest emissions trading system, more than doubled over the past five years, increasing from approximately 30 dollars per ton in 2019 to over 60 dollars per ton in 2024. The price is projected projected to grow further as the EU continues to decrease the emissions cap (Pahle et al., 2022). Rising carbon prices are also a key element of proposed climate policy in the U.S. The Clean Competition Act, currently before the U.S. congress, would impose a carbon tax on carbon-intensive manufacturing firms that grows at 5 percent per year. Our results predict that such policies will reduce the long-run interest rate if the carbon price grows faster than price of the slowest growing fossil fuel in the long run. As the growth rate of the carbon price increases relative to the growth rates of the fossil-energy prices, so does its effect on the long-run interest rate.

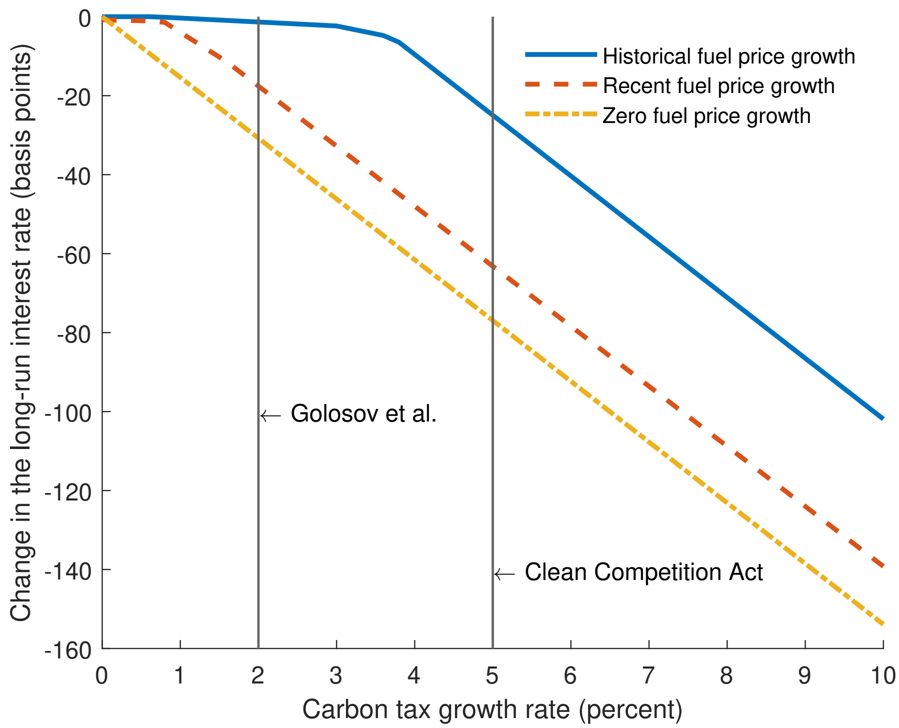
2.5 Quantitative Implications

We parameterize the model to quantify the effect of a carbon tax on the long-run interest rate. We set the factor share of energy in gross output $\nu = 0.085$ (Casey, 2024), the factor share of capital in value added $\tilde{\alpha} = 0.33$ (Jones, 2016), and the inverse of the inter-temporal elasticity of substitution, $\sigma = 1.5$ (Barrage, 2020).

We use data from the EIA to calculate the factor share of each energy type in the production of energy services (the γ's) and the growth rates of fossil-energy prices, $g_{p^i}, i \in \{1, 2, 3\}$. We measure the factor shares of the three types of fossil energy as the ratios of total expenditures on coal (series id CLTCV), natural gas (series id NGTCV), and oil (series

[5]For information on carbon prices around the world, see the Allowance Price Explorer put together by the International Carbon Action Partnership: www.icapcarbonaction.com/en/ets-prices

Figure 1: Effect of a Carbon Tax on the Long-Run Interest Rate



Note: The figure plots the change in the long-run interest rate as a function of the growth rate of the carbon tax for three different assumptions about the long-run growth rates of fossil fuel prices: (1) fossil fuel prices grow at their average rates over the full historical period, 1974 - 2022, (blue line), (2) fossil fuel prices growth at their average rates over the past ten years, 2012-2022 (orange line), and (3) fossil fuel prices are constant (yellow line). The vertical lines show the implied optimal growth rate from Golosov et al. (2014) in our setting, and the growth rate of the carbon price in the proposed Clean Competition Act.

id PATCV) relative to total end-use energy expenditures (series id TETXV). While we do not directly observe expenditures on clean energy, they are included in total end-use energy expenditures. Therefore, we can measure the factor share of clean energy as the residual: $\gamma_0 = 1 - \gamma_1 - \gamma_2 - \gamma_3$.

We measure the real price per unit of carbon emissions for fossil energy type i where $i \in \{\text{coal, oil, natural gas}\}$ as the ratio of total expenditures on fossil energy type i divided by total emissions from fossil energy type i, deflated by the GDP deflator.[6] We calculate the average real growth rates of fossil-energy prices and the average values of the factor shares over two separate time periods: (1) the full historical record (1974-2022) and (2) the past ten years (2012-2022).

Figure 1 plots the change in the long-run interest rate, measured in basis points, as

[6]Data on emissions by fossil fuel type can be downloaded from: https://www.eia.gov/totalenergy/data/browser/csv.php?tbl=T11.01.

a function of the growth rate of the carbon tax. We plot these effects for three plausible assumptions about the long-run growth rates of fossil-energy prices: (1) the long-run growth rates equal the historical averages (blue line), (2) the long-run growth rates equal the averages over the previous decade (orange line) and (3) the long-run growth rates are zero (yellow line).[7] We consider carbon tax growth rates between zero and 10 percent. For context, the vertical lines plot 2 percent and 5 percent as benchmarks to help interpret magnitudes. Golosov et al. (2014) find that on the optimal path, the carbon tax grows at the rate of growth of GDP per capita. In our setting, focused on the U.S., this would equal approximately two percent. The Clean Competition Act in Congress proposes a performance standard for carbon-intensive industries in the U.S. with a carbon tax for dirty producers that grows at approximately 5 percent.

The quantitative impact of the carbon tax on the long-run interest rate increases with the growth rate of the carbon tax and decreases with the growth rate of fossil-energy prices. For example, if fossil-energy prices grow at their historical rates, then a carbon tax that grows at 2 percent will reduce the long-run interest rate by 1 basis point, while a carbon tax that grows at 5 percent will reduce the long-run interest rate by 25 basis points. If instead fossil-energy prices are constant, then a carbon tax that grows at 2 percent will reduce the long-run interest rate by 30 basis points instead of by only 1 basis point, and, a carbon tax that grows at 5 percent will reduce the long-run interest rate by 77 instead of 25 basis points.

3 Extensions

3.1 Least-Cost Net-Zero Climate Policy

Thus far, we have studied the effect of a carbon tax with a range of different growth rates on the long-run interest rate. We next consider the impact on r^* from a carbon tax designed to achieve net zero emissions. Specifically, we impose that the carbon tax must limit cumulative emissions below an exogenous target:

$$\sum_{t=0}^{\infty} \sum_{i=1}^{3} E_t^i \leq \sum E^{\text{Target}}. \tag{23}$$

This constraint requires the economy to achieve net-zero emissions before fully depleting the carbon budget, E^{Target}.

[7] We set the factor shares equal to their average values over the full historical record for cases (1) and (3) and to the average values over the past decade for case (2).

A social planner in this context chooses sequences of consumption, investment, and energy to maximize the present discounted value of lifetime utility subject to the resource constraint and the carbon budget. The addition of the carbon budget to this otherwise standard optimization problem implies that much of the intuition from the standard Hotelling (1931) problem of optimal resource management applies (see Hassler et al. (2021) for a recent treatment). Usually, constraint (23) is interpreted as the limit on the quantity of a natural resource, like oil, that is left in the ground. Here, it captures the remaining carbon budget allowable under a climate policy goal. The solution to the Hotelling (1931) problem is well know and implies that the gap between marginal product and marginal extraction costs should rise at the rate of interest. In the usual case where a forward-looking producer owns the resource stock, this gap between price and marginal cost is the scarcity rent earned by the owner of the natural resource. Here, no agent 'owns' the atmosphere. Instead, there is an externality, and the gap between marginal product and price is equal to the corrective tax along the optimal path.

Proposition 2. *Consider the social planner problem described above. The optimal allocation can be implemented with a tax*

$$\tau_t^{nz} = \beta^{-t} C_t^{\sigma} \Omega, \tag{24}$$

where Ω is the multiplier attached to the emissions constraint. This tax grows at rate

$$g_{\tau}^{nz} = r_{nz}^{*}, \tag{25}$$

where r_{nz}^{*} is the interest rate in the decentralized equilibrium along the optimal path to attain net zero.

The net-zero tax, τ^{nz}, is a Pigouvian tax, where the social cost of fossil energy use is given by the shadow value of the carbon budget measured in units of discounted marginal utility. Discounting implies that this value rises over time at the rate of interest.

We use Proposition 2 to solve for r_{nz}^{*} under the net-zero tax. First, we combine (18) -(20)

to derive r^*_{nz} as a function of g_τ,

$$\ln(1+r^*_{nz}) = \psi - \frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu}$$
$$\times \begin{cases} \gamma_0 \ln(1+g_{p^0}) + \sum_{i=1}^{3} \gamma_i \ln(1+g_{p^i}) & \text{if } g_{p^1} > g_\tau \\ \gamma_0 \ln(1+g_{p^0}) + \gamma_1 \ln(1+g_\tau) + \sum_{i=2}^{3} \gamma_i \ln(1+g_{p^i}) & \text{if } g_{p^2} > g_\tau \geq g_{p^1} \\ \gamma_0 \ln(1+g_{p^0}) + \sum_{i=1}^{2} \gamma_i \ln(1+g_\tau) + \gamma_3 \ln(1+g_{p^i}) & \text{if } g_{p^3} > g_\tau \geq g_{p^2} \\ \gamma_0 \ln(1+g_{p^0}) + \sum_{i=1}^{3} \gamma_i \ln(1+g_\tau) & \text{if } g_\tau \geq g_{p^3}, \end{cases} \tag{26}$$

where $\psi \equiv \frac{\sigma}{1-\tilde{\alpha}}(1-\tilde{\alpha})\ln(1+g_A) - \ln\beta$ is common to all cases. Then, we can use the result that $g_\tau^{nz} = r^*_{nz}$ to numerically solve (26) for the r^*_{nz} under the net-zero carbon tax. This differs from the exercise in Section 2, because the growth rate of the carbon tax is now endogenous to r^*.

The solution for r^*_{nz} requires us to choose values for the growth rate of technology g_A, the growth rate of the clean energy price g_{p^0}, and the discount factor β, in addition to the calibrated values of the other parameters and growth rates from Section 2. We consider the same three cases for the long-run growth rates of fossil-energy prices as in Section 2. We choose β in each case so that r^* in the absence of a carbon tax equals 0.04. We set the growth rate of clean energy prices equal to zero, consistent with the patterns over the past decade (Lazard, 2023), and we set the growth rate of technology equal to 2 percent.

Table 1 reports the growth rate of the net-zero tax (column 1) and the impact of the net-zero tax on r^* (column 2) for the different assumptions about the long-run growth rates of fossil-energy prices. Across the three cases we consider, the effect of a net-zero policy reduces r^* by between 8 and 54 basis points. The net-zero tax has the biggest effect on r^* when fossil-energy prices are constant, because the differences between the growth rate of tax and the growth rates fossil-energy prices are largest in this case.

Importantly, the effect of a net-zero tax on the long-run interest rate does not depend on the temperature target, or equivalently, the size of the carbon budget. From (24), we can see that the carbon budget affects the level of the tax and hence the level of consumption. However, (25) reveals that the carbon budget has no effect on the growth rate of the tax. Since the impact of the tax on r^* in (26) depends only on the growth rate of the tax, it follows that a net-zero policy will have the same impact on r^*, regardless of the carbon budget.

Table 1: Effect of a Net-Zero Carbon Tax on r^*

	g_τ^{nz} (percent)	Δr^* (basis points)
Fossil-energy prices grow at historical rates	3.92	-8
Fossil-energy prices grow at recent rates	3.58	-42
Fossil-energy prices are constant	3.46	-54

Note: The table reports the growth rate of the carbon tax that attains net zero (column 1) and the resulting change in the long-run interest rate (column 2) for the same three assumptions about the long-run run growth rates of fossil-energy prices as in Figure 1.

3.2 Clean-Energy Subsidy

While the analysis thus far has focused on carbon taxes, much of US climate policy takes the form of subsidies to clean energy. For example, the Inflation Reduction Act (IRA) provides subsidies to solar and wind electricity generation (Bistline et al., forthcoming). The intuition for the effect of a subsidy on the long-run interest rate is opposite that of a tax. A clean energy subsidy slows the growth of energy prices, which, in turn, increases the growth of TFP and the long-run interest rate.

We adopt the analysis from Section 2 to study the effect of a clean-energy subsidy on r^*. Instead of a carbon tax, we impose a subsidy, s_t, for clean energy that grows at rate g_s. The subsidy-inclusive price of clean energy at time t is $p_t^0 - s_t$. The subsidy is financed with a lump-sum tax on households. We use the same steps as in Section 2 to derive the growth rate of energy prices on the ABGP as a function of the subsidy and the growth rate of the clean energy price:

$$\ln(1+g_{P_E}^*) = \begin{cases} \gamma_0 \ln(1+g_{p^0}) + \sum_{i=1}^3 \gamma_i \ln(1+g_{p^i}) & \text{if } g_{p^0} > g_s \\ \gamma_0 \ln(1-g_s) + \sum_{i=1}^3 \gamma_i \ln(1+g_{p^i}) & \text{else.} \end{cases} \tag{27}$$

The effect of the subsidy on rstar equals:

$$\Delta r^* \approx \begin{cases} 0 & \text{if } g_{p^0} > g_s \\ \frac{\sigma}{1-\tilde{\alpha}} \times \frac{\nu}{1-\nu} \times \gamma_0 (g_s - g_{p^0}) & \text{else.} \end{cases} \tag{28}$$

In this setting, the growth rate of the price of energy services depends on the growth rate of the subsidy-inclusive clean-energy price and on the growth rates of the price of each type of fossil energy. On the ABGP, the growth rate of the subsidy-inclusive clean-energy price will either equal the growth rate of the clean-energy price or the growth rate of the subsidy, whichever is largest. Thus, a clean-energy subsidy will only affect r^* if the growth rate of the subsidy exceeds the growth rate of the clean-energy price. In this case, the subsidy-inclusive price of clean energy falls over time and becomes negative in the long run. The falling price of clean energy reduces the growth rate of the price of energy services, raising TFP growth and thus pushing up r^*.

3.3 Elasticity of Substitution Between Clean and Fossil Energy

In our main analysis, we set the elasticity of substitution between clean energy and fossil energy in equation (2) equal to unity. This choice is necessary for balanced growth and is consistent with Golosov et al. (2014) and with time series evidence from Casey and Gao (2023). Yet several empirical studies suggest higher elasticities (see e.g., Papageorgiou et al., 2017). Additionally, technological advances, such as improvements in battery storage, could raise the elasticity of substitution between clean and fossil energy in the future.

Increases in the elasticity of substitution will affect our qualitative results if it becomes so high that fossil energy is no longer an essential input in the production of energy services. A linear production function is the extreme example of this case; neither input is essential and the elasticity of substitution is infinite. When fossil energy is not essential, the impact of the carbon tax on the long-run interest rate depends on whether the tax is large enough to trigger a complete switch from fossil to clean energy. If the tax is not large enough, then the analysis from Section 2 continues to hold and the impact of the tax on the long-run interest rate depends on how the growth rate of the tax compare to the growth rate of fossil fuel prices. If instead, the tax is large enough to trigger the switch, then the growth rate of the price of energy services equals the growth rate of the price of clean energy. Apart from triggering the switch, the tax has no impact on TFP growth or the long-run interest rate.

4 Conclusion

We develop a simple growth model to study the impact of climate policy on the long-run interest rate. Overall, we find that a carbon tax will decrease the long-run interest rate if the growth rate of the tax exceeds the growth rate of the price of at least one type of fossil fuel. Similarly, we find that a clean-energy subsidy will increase the long-run interest rate if the growth rate of the subsidy exceeds the growth rate of the clean energy price.

We explore the implications of a carbon tax that achieves net zero emissions. We find that such a tax could reduce the long-run interest rate between 8 and 54 basis points for plausible assumptions about the long-run growth rates of energy prices. These results suggest that climate policy could have important implications for financing the green transition and for monetary policy. A decrease in the long-run interest rate could increase the relative return to investing renewable energy, which is more capital intensive that fossil sources. Moreover, a 50 basis point decrease in the long-run interest rate represents approximately one sixth of the historical decline and would imply that policymakers need to make two additional rate cuts to stabilize the federal funds rate at the neutral level. Understanding the implications of climate policy for the long-run interest rate is particularly important for monetary policymakers because it is difficult to estimate the long-run interest rate in real time.

Our research points to a number of interesting avenues for future work. For example, we focus on the direct effect of climate policy on long-run consumption growth. Other work has instead focused on the effect of physical climate risk on the long-run interest rate (see e.g., Hambel et al., 2024; Bylund and Jonsson, 2020). Ultimately these two channels are linked; effective climate policy should reduce climate risk and other types of climate damage. This feedback could have interesting implications for the long-run interest rate.

5 Appendix

5.1 Net-Zero Carbon Tax

Since the solution to this problem is well-known, we provide a relatively quick proof. The strategy is to derive the first-order conditions for the optimal allocation and then compare them to first-order conditions for the decentralized equilibrium. In the absence of policy, the decentralized equilibrium ignores the dirty energy use target, E^{target}. This is the only market failure, and it can be corrected with a Pigouvian tax on on dirty energy. The marginal external cost of dirty energy is equal to the shadow value on the constraint imposed by the target.

The Lagrangian for the social planner's problem can be written as

$$\mathcal{L} = \sum_{t=0}^{\infty} \beta^t u \left(K_t^{\alpha} \left(A_t L_t\right)^{1-\alpha-\nu} \left(\prod_{i=0}^{3} (E_t^i)^{\gamma_i} \right)^{\nu} - \sum_{i=0}^{3} p_t^i E_t^i - K_{t+1} + (1-\delta) K_t \right) - \Omega \left(\left(\sum_{t=0}^{\infty} \sum_{i=1}^{3} E_t^i \right) - E^{\text{Target}} \right). \tag{29}$$

The first order condition for K_{t+1} is

$$u'(C_t) = \beta(1 + r_{t+1})u'(C_{t+1}), \tag{30}$$

where we have used (7) and (14) to write the result in terms of the interest rate in the decentralized economy.

The first order condition for flow energy use is given by

$$p_t^0 = p_t^E \gamma_0 \left(\frac{E_t}{E_t^d} \right), \tag{31}$$

$$p_t^i + \beta^{-t}(u'(C_t))^{-1}\Omega = p_t^E \gamma_i \left(\frac{E_t}{E_t^d} \right), \quad i = 1, 2, 3, \tag{32}$$

where we have used (2) and (13) to write the results in terms of E_t and p_t^E in the decentralized equilibrium.

Comparing these results to the first order conditions from the decentralized equilibrium, (8) and (10), we observe that the optimal allocation can be implemented with a single instrument:

$$\tau_t^{\text{opt}} = \beta^{-t}(u'(C_t))^{-1}\Omega. \tag{33}$$

Combining this result with (30) gives

$$\frac{\tau_{t+1}^{\text{opt}}}{\tau_t^{\text{opt}}} - 1 \equiv g_\tau^{\text{opt}} = r_{t+1}. \tag{34}$$

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