The effects of climate policy on the real interest rate*

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PRELIMINARY WORK - PLEASE DO NOT CIRCULATE OR CITE

Abstract

A number of studies point out how changing structures in society (ageing, lower population growth, etc.) affect the real interest rate, but nobody has yet taken climate policy into account even though solving the climate problem is a given in the coming years. In a 60-cohort overlapping generations model with two types of capital, I investigate how climate policy and the green transition affect the real interest rate. I find that while production adjusts to a new greener capital stock, the real interest rate increases because of large demands for new capital. At the peak of the transition, the real interest rate is 80 basis points higher than in the baseline.

Keywords: Real interest rate, climate change, green transition

JEL Classification: E43, E47, Q54

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1 Introduction

There is a substantial literature explaining why the historically low real interest rate is the new normal because of changing structures in society - ageing, lower population growth, lower productivity growth, etc (Bernanke 2005; Carvalho et al. 2016). The real interest rate is an important economic variable which affects central banks' abilities to conduct effective monetary policy. Furthermore, low interest rates incentivise debt-taking among consumers and may increase financial vulnerabilities through more risk-taking in asset markets in a search for yield (Bean et al. 2015).

Going forward, climate change mitigation is an important structural factor which is going to affect the real interest rate via carbon taxes, green investments, changes in production technologies, etc.

The question is thus: What are the effects of climate policy and the green transition on the real interest rate? In this paper, I define the real interest rate as the natural rate of return on capital.[1] I build an overlapping generations model with 60 cohorts and two types of capital, green and black. Individuals work for 40 years and are retired for 20 years where the working population pay their pensions. Agents get dis-utility from owning black capital and are thus satisfied with a lower return on green capital.[2] Capital is subject to rigid adjustment via convex adjustment costs. Furthermore, I model a feedback from the climate to the economy in a DICE-type of framework (Golosov et al. 2014; Hassler et al. 2018).

The main result of the paper is that a carbon tax (the first best climate policy) increases the real interest rate - especially during the transition to a greener world. When the production side of the economy needs large amounts of capital to adjust to green policies, the real interest rate increases because of the surge in demand for capital. The effects are heterogeneous such that demand for black capital falls which decreases the black interest rate. At the same time, increasing investments in green capital makes the green interest rate increase. The net effect

[1] In accordance with standards in the literature (see Papetti (2021)), the natural real interest rate is the rate that equalises households' savings and firms' capital demand in the absence of frictions and shocks and implied business cycles.

[2] Individuals' willingness to forego returns on green investments is empirically founded in the ESG finance literature which has established that green returns are about XX% lower than general market returns. See e.g. Berk and Binsbergen (2021).

on the weighted average interest rate is positive during the entire transition.

The magnitude of the increase in the real interest rate (relative to the baseline scenario with only demographic changes) is between 20 and 80 basis points the first 15 years after a shift in the production technology. It is largest in the first years after the shock and then gradually declining. After 30 years, the new interest rate is only slight higher than before and thus the effect is temporary during the transition to a cleaner world. The magnitude of the interest rate increase is comparable to that of demographic change, however somewhat smaller. The literature finds declines in the real interest rate of 80-150 basis points caused by demographics over similar time frames (Papetti 2021; Krueger and Ludwig 2007). These effects are, however, persistent.

After the transition to a world with more green capital, the new average interest rate depends on individuals' green preferences over time. Today, people accept lower returns on green investments. In the model, I capture this with a utility penalty for holding black capital.

The literature on the causal link between climate policy and the real interest rate is almost non-existent. There has been an extensive debate about the importance of the interest rate and discounting for optimal policy (Goulder et al. 2019). But the question here is the opposite: If we implement optimal policy, what is then the effects on the returns to capital - the real interest rate. I have only managed to find a limited number of macro-economic papers concerned with climate change which briefly mention the real interest rate. One is Meijden et al. (2015) who argue that front-loading of fossil fuel supply implies higher current than future output, which in turn increases savings and drives interest rates down. This is a result of expectations of future climate policy which make producers over-exploit current black capital. Another paper which address the real interest rate in a climate change context is Bylund and Jonsson (2020) who discuss the effects of climate change (not climate policy) on the real interest rate. They argue that climate change imply a more risky world and hence higher precautionary savings which depress the real interest rate.

In contrast, the literature has proposed several reasons for the empirically declining and persistently low interest rates. First, famously is the Global Savings Glut hypothesis proposed by Bernanke (2005), which states that ageing implies higher capital to labour ratio which drives the real interest rate down. Secondly, precautionary savings have increased because of the financial crisis, climate change, the corona crisis, etc., which all increase the perceived probability of future economic disaster in line with arguments presented by Barro (2006). Thirdly, the literature has also presented arguments concerned with slower growth rates leading to lower demand for new capital, lower expectations of future growth, which lowers incentives to borrow (Elmendorf and Sheiner 2017), income in-equality redistributing wealth from spenders (low-income) to savers (high-income), and new production types which are less capital intensive than old technologies which also leads to low demand for capital [ref].

The literature is thus well-founded on several other determinants of the real interest rate. Nevertheless, climate policy is an important factor in the coming century which will affect economies all over the world. The paper rest of the paper is structured as follows. In Section 2, I present the numerical overlapping generations model. Section 3 describes the calibration. In section 4, I present the simulation of a uniform carbon tax on black capital. Section 5 concludes.

2 Model

In this section, I present an overlapping generations model (OLG) for a closed economy with 60 cohorts in the style of e.g. Papetti (2021), Domeij and Floden (2006), and Krueger and Ludwig (2007), but with two capital stocks - green and black - and feedback from the climate. I consider a closed economy because I am interested in the overall effects of climate policy in the world/Eurozone. In general, papers find the same interest rate effects no matter if they investigate dis-aggregated regional models or closed economy world models[3]. I build in important climate properties in the spirit of the dynamic integrated assessment models (Nordhaus 1991; Hassler et al. 2018). I include a feedback between the climate and the economy and adjustment costs of capital. Agents live for 60 periods, work for the first 40 periods, and are retired for the last 20 periods. I include pensions and survival rates so I can evaluate climate policy in a setup with other important factors affecting the real interest rate - changes to fertility and mortality rates and implied varying cohort sizes.

2.1 Households

The model consists of J(=60 in the baseline specification) cohorts containing $N_{t,j}$ individuals aged j at time t. The cohorts develop according to

$$N_{t,j} = N_{t-1,j-1} s_{t+j,j}$$

Where $s_{t,j}$ is the conditional survival probability of surviving from period $j-1$ to period j. Each households maximises lifetime utility choosing consumption and savings

$$U = \sum_{j=0}^{J} \beta^j \pi_{t+j,j} \left(\frac{(c_{t+j,j})^{1-\sigma_c}}{1-\sigma_c} - \omega_k \frac{(k^b_{t+j,j})^{1-\sigma_k}}{1-\sigma_k} \right) \tag{1}$$

Here $\pi_{t+j,j} = \Pi_{k=0}^{j} s_{t+k,k}$ is the unconditional survival probability, β is the discount factor, $c_{t+j,j}$ is the consumption at time $t+j$ for an individual at age j, and $k^b_{t+j,j}$ is the black capital stock at time $t+j$ from which the individual derives dis-utility. Empirically, this seems plausible - recently there has been large rises in investments in ESG funds. Thus, individuals seem to have preferences for green capital even though ESG investment in itself does not affect pollution, see e.g. Berk and Binsbergen (2021) and Heinkel et al. (2001).

[3]See Papetti (2021) for a discussion of this.

Individuals maximise their utility subject to a standard budget condition, where they spend their income on either consumption or investments in the capitals stocks, which they own and get interest payments from by renting it out to the firms. They also pay a fraction of the adjustment costs of capital corresponding to how much of the capital stock they own[4]. The budget constraint for the cohort aged j at time t looks the following

$$\begin{aligned} N_{t,j} y_{t+j,j} + (1 + r_t^b - \delta^b) k^b_{t+j-1,j-1} + (1 + r_t^g - \delta^g) k^g_{t+j-1,j-1} \\ = k^b_{t+j,j} + k^g_{t+j,j} + c_{t+j,j} + \sum_i Adj^i_{t+j} \cdot \nu^i_{t+j,j}. \end{aligned}$$

Capital depreciates with the rates δ^b and δ^g and owners pay adjustment costs if they adjust the capital stocks with more than the depreciated shares. Importantly, capital adjustment costs are payed on the adjustment of the aggregate capital stock, $K^i_{t+j} = \sum_{k=1}^J k^i_{t+j,k} N_{t+j,k}$, and not the capital stocks owned by each cohort. This reflects that adjustment of capital is costly on the production side and not because capital ownership changes. The adjustment costs are convex such that small changes are relatively cheap. The adjustment costs are modelled according to the following

$$Adj^i_{t+j} = \frac{\phi}{2} \left(\frac{K^i_{t+j}}{K^i_{t+j-1}} - 1 \right)^2 K^i_{t+j}, \quad i \in \{b, g\}.$$

The share of the adjustment costs that an individual in cohort j pays is

$$\nu^i_{t+j,j} = \left(\frac{k^i_{t+j,j} s_{t+1}}{K^i_{t+j}} \right).$$

The income $y_{t+j,j}$ of an individual aged j at time $t + j$ is

$$y_{t+j,j} = (1 - \tau) w_{t+j} h_{t+j,j} I_{j<j_r} + \psi \cdot w_{t+j_r-1} \bar{h} I_{j \geq j_r}.$$

Thus, the agents get paid the after tax wage w_{t+j} for the number of hours that they work $h_{t+j,j}$ if they are below the retirement age j_r and they get a pension which is equal to a fraction of the wage when they retired. The pension is financed with a tax on the working population. See Section 2.5.

[4]There is thus an externality because individuals only pay a fraction of the adjustment costs and thus they do not internalise the entire cost.

The households maximise their utility subject to their budget choosing consumption $(c_{t+j,j})$, green savings (k_t^g), and black savings (k_t^b) The Lagrangian of the maximisation problem reads

$$\mathcal{L} = \sum_{j=0}^{J} \beta^j \pi_t \left(\frac{(c_{t+j,j})^{1-\sigma_c}}{1-\sigma_c} - \omega_k \frac{(k_t^b)^{1-\sigma_k}}{1-\sigma_k} \right)$$
$$+ \lambda_{t+j,j} \left[y_{t+j,j} - c_{t+j,j} + \sum_{i\in\{b,g\}} \left((1+r_t^i - \delta^i) k^i_{t+j-1,j-1} - k^i_{t+j,j} - \frac{\phi}{2} \left(\frac{K^i_{t+j}}{K^i_{t+j-1}} - 1 \right)^2 K^i_{t+j} \cdot \nu^i_{t+j,j} \right) \right]$$

Assume that the consumers consider the share that distributes the adjustment costs among them as exogenous. I.e. consumers do not take into account changes in this share when they choose optimal amounts of capital. Then we have the following intertemporal first order conditions

$$\frac{\partial \mathcal{L}}{\partial c_{t+j,j}} = \beta^j \pi_{t+j,j} c_{t+j,j}^{-\sigma_c} - \lambda_{t+j,j} = 0$$
$$\frac{\partial \mathcal{L}}{\partial k^b_{t+j,j}} = \beta^j \pi_{t+j,j} \omega_k (k^b_{t+j,j})^{-\sigma_k} + \lambda_{t+j,j} \left[1 + \nu^i_{t+j,j} \cdot K^b_{t+j} \phi \left(\frac{K^b_{t+j}}{K^b_{t+j-1}} - 1 \right) \frac{s_{t+j,j}}{K^b_{t+j-1}} + \frac{\phi}{2} \left(\frac{K^b_{t+j}}{K^b_{t+j-1}} - 1 \right)^2 s_{t+j,j} \right]$$
$$- \lambda_{t+j+1} \left[1 - \delta^b + r^b + \nu^i_{t+j,j+1} \phi \left(\frac{K^b_{t+j+1}}{K^b_{t+j}} \right)^2 s_{t+j,j} \left(\frac{K^b_{t+j+1}}{K^b_{t+j}} - 1 \right) \right] = 0$$
$$\frac{\partial \mathcal{L}}{\partial k^g_{t+j,j}} = \lambda_{t+j,j} \left[1 + \nu^i_{t+j,j} \cdot K^g_{t+j} \phi \left(\frac{K^g_{t+j}}{K^g_{t+j-1}} - 1 \right) \frac{s_{t+j,j}}{K^g_{t+j-1}} + \frac{\phi}{2} \left(\frac{K^g_{t+j}}{K^g_{t+j-1}} - 1 \right)^2 s_{t+j,j} \right]$$
$$- \lambda_{t+j+1} \left[1 - \delta^g + r^g + \nu^i_{t+j,j+1} \phi \left(\frac{K^g_{t+j+1}}{K^g_{t+j}} \right)^2 s_{t+j,j} \left(\frac{K^g_{t+j+1}}{K^g_{t+j}} - 1 \right) \right] = 0$$

Eliminating the λ's, we get the Euler conditions for black savings

$$\omega_k (k^b_{t+j,j})^{-\sigma_k} + c_{t+j,j}^{-\sigma_c} \left[1 + \nu^i_{t+j,j} \cdot K^b_{t+j} \phi \left(\frac{K^b_{t+j}}{K^b_{t+j-1}} - 1 \right) \frac{s_{t+j,j}}{K^b_{t+j-1}} + \frac{\phi}{2} \left(\frac{K^b_{t+j}}{K^b_{t+j-1}} - 1 \right)^2 s_{t+j,j} \right]$$
$$- \beta s_{t+j+1,j+1} c_{t+j+1,j+1}^{-\sigma_c} \left[1 - \delta^b + r^b + \nu^i_{t+j,j+1} \phi \left(\frac{K^b_{t+j+1}}{K^b_{t+j}} \right)^2 s_{t+j,j} \left(\frac{K^b_{t+j+1}}{K^b_{t+j}} - 1 \right) \right] = 0$$

And for green savings

$$c_{t+j,j}^{-\sigma_c} \left[1 + \nu^i_{t+j,j} \cdot K^g_{t+j} \phi \left(\frac{K^g_{t+j}}{K^g_{t+j-1}} - 1 \right) \frac{s_{t+j,j}}{K^g_{t+j-1}} + \frac{\phi}{2} \left(\frac{K^g_{t+j}}{K^g_{t+j-1}} - 1 \right)^2 s_{t+j,j} \right]$$
$$- \beta s_{t+j+1,j+1} c_{t+j+1,j+1}^{-\sigma_c} \left[1 - \delta^g + r^g + \nu^i_{t+j,j+1} \phi \left(\frac{K^g_{t+j+1}}{K^g_{t+j}} \right)^2 s_{t+j,j} \left(\frac{K^g_{t+j+1}}{K^g_{t+j}} - 1 \right) \right] = 0$$

The consumer's optimality conditions are the two Euler conditions together with the budget constraint and the initial capital stocks.

2.2 Firms

Consider a representative firm which produces with labour, L green capital, K^g, and black capital, K^b, according to a nested CES function

$$y_t = A_t \left[\alpha_1^{1/\epsilon} \cdot (L_t)^{(\epsilon-1)/\epsilon} + (1-\alpha_1)^{1/\epsilon} \cdot \left(\hat{K}_{t-1} \right)^{(\epsilon-1)/\epsilon)} \right]^{(\epsilon/(\epsilon-1))}$$

$$\hat{K}_t = \left[\alpha_2^{1/\gamma} \cdot \left(K_t^b \right)^{(\gamma-1)/\gamma} + (1-\alpha_2)^{1/\gamma} \cdot (K_t^g)^{(\gamma-1)/\gamma)} \right]^{(\gamma/(\gamma-1))}$$

Here, α_1 and α_2 are the CES shares of the capital-labour nest and the all capital nest, ϵ is the substitution elasticity between capital and labour, and γ is the substitution elasticity between green and ordinary capital. A is endogenous and is a function of temperature and technology growth. See Section 2.4. Firms maximise per period profits

$$\Pi = y_t - w_t L_t - \hat{r}_t \hat{K}_{t-1} = y_t - w_t L_t - r_t^b K_{t-1}^b - r_t^g K_{t+j-1,j-1}^g$$

Where the price of y is the numeraire. The total number of working ours, L_t is exogenously given and is equal to the sum of the working hours of the population below the retirement age

$$L_t = \sum_{j=0}^{j_r} N_{t+j,j} h_{t+j,j}$$

Maximising profits yields the following demands for labour and capital

$$L_t = A_t^\epsilon \cdot \alpha_1 \cdot y_t \cdot \left(\frac{1}{w_t} \right)^\epsilon$$

$$\hat{K}_{t-1} = A_t^\epsilon \cdot (1-\alpha_1) \cdot y_t \cdot \left(\frac{1}{\hat{r}_t} \right)^\epsilon$$

In the capital sub-nest, the demand for the two types of capital is

$$K_{t+j-1,j-1}^b = \alpha_2 \cdot \hat{K}_{t-1} \cdot \left(\frac{\hat{r}_t}{r_t^b} \right)^\gamma$$

$$K_{t+j-1,j-1}^g = (1-\alpha_2) \cdot \hat{K}_{t-1} \cdot \left(\frac{\hat{r}_t}{r_t^g} \right)^\gamma$$

2.3 The carbon cycle

The use of black capital emits carbon proportional to the size of the capital stock. Intuitively, this might be because black capital uses energy, fuel, etc. Emissions are thus given by

$$M_t = d \cdot K_t^b,$$

Where d scales the amount of emissions per capital unit.

I follow Golosov et al. (2014) and Hassler et al. (2018) and assume the following development of the atmospheric carbon stock

$$S_t = \sum_{s=0}^{t} (1 - \delta_s^E) M_{t-s}$$

where

$$(1 - \delta_s^E) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s$$

is the amount of carbon remaining in the atmosphere at time s. Here, φ_L denotes the share that is in the atmosphere forever. In the remaining share, $1 - \varphi_L$, a share of $1 - \varphi_0$ leaves the atmosphere after 1 period, whereas the rest depreciates geometrically in accordance with the expression above.

2.4 The economic damages from the climate

Assume that global warming affects temperature through its effect on the total factor productivity, A. The effect of emissions on global warming is logarithmic and thus can be expressed as

$$T_t = \frac{\lambda}{\ln(2)} \ln\left(\frac{S_t + \bar{S}}{\bar{S}}\right).$$

Here λ is the climate sensitivity and $\bar{S}$ is the pre-industrial atmospheric carbon stock. I use the same specification for the total factor productivity as Golosov et al. (2014) and set

$$A_t = e^{z_t - \Gamma_t T_{t-1}}$$

Here z_t is technological change.

2.5 Government and taxes

The government collects a tax to fund the pay-as-you-go pension which all individuals above the retirement age get. The tax is set such that the current population pays for the pension which has a fixed replacement rate, meaning that e.g. ageing leads to a higher tax rate.

$$\tau_t = \frac{\sum_{j=j_r}^{J} \psi \cdot w_{t+j_r-1}\bar{h} \cdot N_{t,j}}{w_t(\sum_{j=1}^{j_r-1} N_{t,j})}$$

The numerator is the total amount of pensions at time t whereas the numerator is the value of all worked hours at time t.

2.6 Policy and shocks

Any government has different policy tools for solving the climate problem. The first best solution is to implement a uniform carbon tax equal to the social cost of carbon (see e.g. Nordhaus (2019)). As I abstract from any cooperation failures, it is possible to reach the first best in my setup. Thus, the difficult question is not *what* the optimal solution to the problem of climate change is, but how large the social cost of carbon is. In the academic literature there is not consensus about this - cf. the discrepancy between estimates from Stern (2007) and Nordhaus (2007) which in the end comes down to different social discount rates. I.e. how much weight do we put on future vs current cohorts?

I implement uniform carbon taxes of different magnitudes to evaluate the effects (both qualitatively and quantitatively) on the real interest rate. I evaluate this in both the ”pure” model and with other factors affecting the real interest rate - longevity and fertility projections.

There are of course also other green policies i.e. general abatement, subsidies, etc. Depending on the implementation of these, they might affect the real interest rate differently. Common for these, however, is that they are sub-optimal policies which will make the green transition more expensive than the first best.

3 Calibration

In this section, I present the parameter choices of the model. See Table 1 for a comprehensive list of all parameters.

Starting with the utility parameters, I set the parameter of relative risk aversion of consumption θ_c to 0.8. This corresponds to an intertemporal elasticity of substitution of 1.25. The empirical literature suggests that the elasticity of substitution is lower. In a meta analysis, Havranek et al. (2015) finds that the elasticity should be 0.5 based on 2735 estimates from 169 studies. However, I choose a higher elasticity to ensure that the income effect does not dominate the substitution effect when interest rates change. For lower substitution rates, individuals are incentivised to lower their savings when interest rates increase because of the income effect which makes them better off as retirees with higher interest payments. Thus, to ensure more realistic savings patterns and responses, I increase the intertemporal elasticity of substitution.

I set a yearly discount factor of 0.96 which together with the initial survival probabilities gives a baseline real interest rate of 5.34%.

I set the utility weight of green capital ω_k to 0.001 which corresponds to an interest rate spread of 16 basis points.

For the firm parameters, I set the depreciation of green and black capital to 9.5% yielding an investment to output ratio of 0.15 in the initial steady state. This is in line with e.g. Papetti (2021) and Gomes et al. (2012) who set δ equal to 0.0952 and 0.0963. In the capital and labour nest, I choose the CES production function weight of labour to 0.667.

I set the CES production function weight of black capital equal to 0.32 such that black capital constitutes 30% of capital in the baseline scenario. IEA (2021) has estimated that capital investments should increase with 1 percentage point on average over 30 years for the world to reach climate neutrality. Under a 10 percent depreciation rate, this corresponds to 10% of GDP investments over 30 years. As the world capital stock corresponds to 30% of GDP in baseline, this implies that around one third of the capital stock is new due to the green transition. Thus, we can calibrate the black capital stock as one third of the existing capital stock in baseline. (WIP)

For the elasticity of substitution, I choose complementarity between labour and capital ($\epsilon = 0.8$) which is in line with empirical studies suggest. See e.g. Chirinko (2008) who finds that the elasticity of substitution between labour and capital is between 0.4 and 0.6. There is however, not consensus in the literature about this elasticity and thus I will return to this in the sensitivity analysis. For the substitutability between black and green capital, I choose $\gamma = 2$ in baseline such that black and green capital are substitutes highlighting that their main difference is in the climate properties. The adjustment parameter on capital adjustments is 16. This parameter only matters for adjustment trajectories and not the final steady states. An adjustment cost parameter of 16 is standard in the macro literature implying an adjustment speed of around 6.7% per year (see Summers et al. (1981)).

The model has a single policy parameter, the replacement rate for pensions, which I set to 0.667 meaning that retirees get two thirds of their retirement wage in pensions. Kara and von Thadden 2016 choose 0.45.

For the climate parameters, I follow Golosov et al. (2014) and set the fraction of emissions that stay in the atmosphere for more than one period to 0.393. The depreciation rate of emissions is 0.0228. The baseline emission stock is 581 giga tonnes of carbon (GtC). I set the temperature sensitivity to emissions to 2 which is in the interval provided by the IPCC (2014). They argue that the sensitivity lies between 1.5 and 4.5°C. I set the sensitivity of the economy to the climate to 1. I calibrate the emission intensity such that current temperature is 1.1 degree above pre-industrialised levels in accordance with NASA (xx).

Table 1: Baseline parameter specification

ω_k	Weight on capital in utility function	0.001
σ_c	Relative risk aversion parameter of consumption	0.8
σ_g	Relative risk aversion parameter of black capital	0.8
β	Discount factor	0.96
δ^g	Depreciation of green capital	0.095
δ^b	Depreciation of black capital	0.095
α_1	Weight on labour in production	0.667
α_2	Weight on black capital	0.32
ϵ	Elasticity of substitution between labour and capital	0.8
γ	Elasticity of substitution between black and green capital	2
ϕ	Adjustment parameter on capital	16
ψ	Replacement rate for pensions	0.667
d_0	Fraction of emissions that stay more than 1 period	0.393
δ^E	Depreciation rate of emissions	0.0228
$\bar{S}$	Baseline emission stock (industrialised level)	581 GtC
λ	Temperature sensitivity to emissions	2
Γ	Sensitivity of the economy to the climate	1
z	Technology growth	0.01

4 Introduction of a carbon tax increases the interest rate

In this section, I report the projections of the real interest rate after uniform carbon tax on emissions from black capital. In the first subsection, I show the results without any additional transition, i.e. the clean effect from the shock. In the second subsection, I include the demographic transition for comparability. The green transition is thus happening in addition to the demographic transition, which is known to affect the real interest rate via several channels. Papetti (2021) finds that demographics account for about 1.4 percentage points decrease of the natural real interest rate from 1980 to 2030, which is in line with Krueger and Ludwig (2007) who find a real interest rate decrease of 86 basis points between 2005 and 2080 caused by an ageing population. In my projections, I include fertility and increased longevity.

4.1 Results without demographics

Figure 1 shows the transition of the economy after an unexpected carbon tax levied on the emissions from black capital.[5] The dashed lines indicate pre-shock "steady state"[6] with an average interest rate of 5.3% and a black capital stock that constitutes 30% of the total capital stock. Temperature is 1.1 degrees above pre-industrial temperature. A general carbon tax policy causes a transition from black to green capital where black capital constitutes only 20% of the total capital stock. See Panel 3c.

Initially after the shock, the green interest rate increases whereas the black interest rate decreases, which corresponds to the large shifts in capital which are now required to produce optimally. The transition does not happen instantly because of convex adjustment costs. During the transition, the two interest rates converge towards their new steady states. The black interest rate goes towards a slightly higher level than the old steady state (a 9 basis points increase) and the green interest rate converges back to its previous levels - corresponding to the new, larger green capital stock. The tax lowers the overall capital stock which implies a decreasing capital to labour ratio. Capital is thus relatively more productive than before the tax (the production function is unaffected), making the interest rates increase. At the

[5] The tax revenue is transferred back to firms.

[6] The economy is not in a real steady state because temperature is increasing which feeds back to the economy.

peak of the transition, the green interest rate is 160 basis points higher than in the baseline state (reaching 6.119%) whereas the black interest rate is 300 basis points lower. The average interest rate is 82 basis points higher at the peak and is above the baseline level during the entire transition and afterwards.

Temperature is kept below the current levels during the entire transition and it provides a positive feedback where the new and lower temperature level positively affects productivity which in turn increases the demand for capital by firms. Importantly, this happens because the model does not feature any inertia, meaning that lower emissions spill over to temperature immediately.

4.2 Results with demographics

The development of the real interest rate is driven by structural factors such as demographics, productivity, inequality, etc. In this section, I present my results in a scenario with changing demographics according to the UN population forecast. See Appendix A for a graph of the changes in the conditional survival probabilities. The world is ageing and thus savings are increasing. This is illustrated with dashed lines in Panel 2c in Figure 2 where both the black and the green capital stock increases in baseline over the next 100 years due to increased demand for savings. The increase in capital results in decreasing interest rates which is what Bernanke (2005) famously termed ”the global savings glut”. This mechanism is independent of climate change or policy.

When I introduce a shock to the economy which incentivises a shift from black to green capital, this happens in addition to the shift towards capital caused by ageing. This is what is depicted with solid lines in Figure 2. The difference between the dashed and solid lines are then the added effect of climate policy. The figure shows the transition after the implementation of a carbon tax on emissions from black capital - i.e. the same shock as in Figure 1. But now, the dashed lines indicate the baseline equilibrium and not the steady state because of changes in survival probabilities of the population which implies that the economy is not in steady state at any point in time. It is hit with survival shocks continuously.

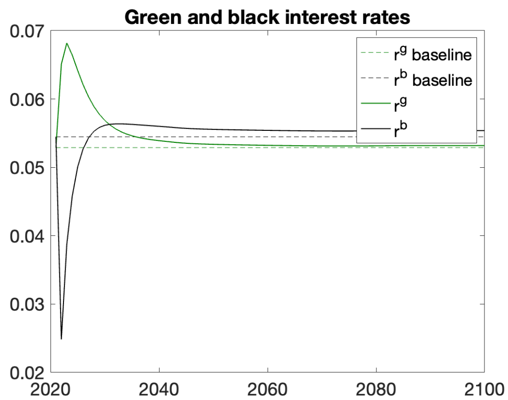
Again, capital changes and the shift in capital are substantially larger than e.g. the general increase in the capital stock caused by ageing. Demographic changes causes capital to increase

5.3% over 80 years (net of general growth) whereas the added climate policy changes this to a decline of 7%.

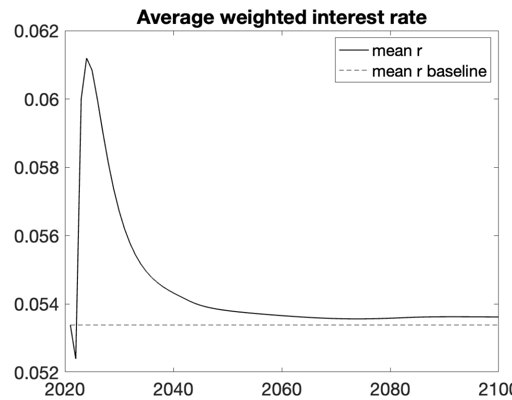
As in the clean model from before, the green interest rate increases significantly, whereas the black drops.

The magnitude of the increase in the real interest rate is between 20 and 80 basis points in the first 15 years after the policy is implemented. The difference is largest immediately after the policy is implemented and then gradually declines. Compared with the magnitude of the demographic transition, which in my simulation provides a lasting decline of the interest rate of 50 basis points, the effect of climate policy is comparable to this effect but is, importantly, temporary. The effects are, however, non-negligible over a period of approximately a generation.

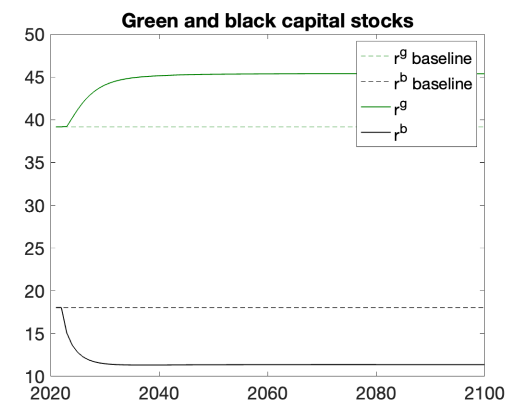
Instead of increasing temperature as in the baseline, the climate tax implies decreasing temperatures which then provides a positive feedback link to the economy.



(a) Green and black interest rates net of depreciation.



(b) The average weighted interest rate net of depreciation.



(c) Capital stocks.

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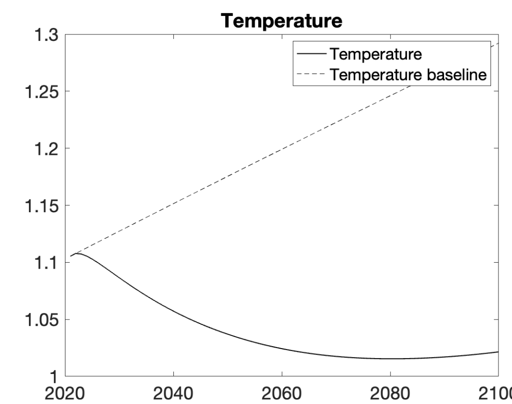
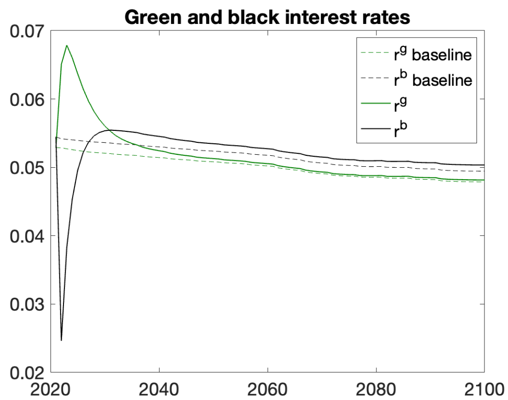
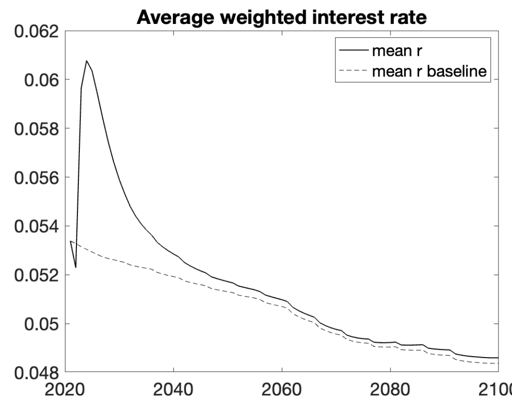


(d) Temperature in degrees celcius above pre-industrial temperature.

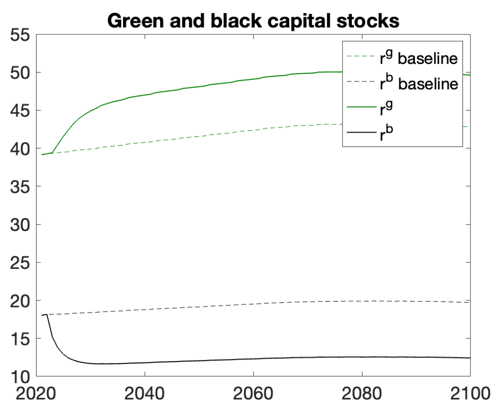
Figure 1: Projections from the cohort model without demographics after a carbon tax on emissions from black capital. The dashed lines indicate the baseline trajectories. Green lines indicate green capital in the plots concerned with two types of capital.



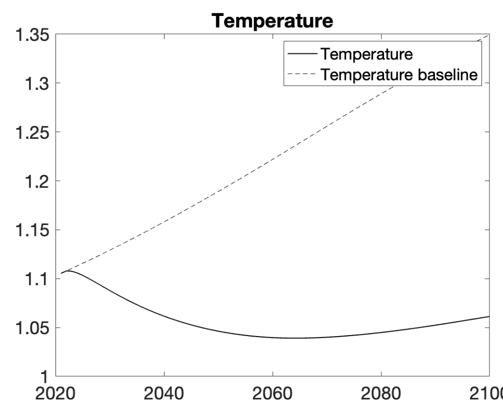
(a) Green and black interest rates net of depreciation.



(b) The average weighted interest rate net of depreciation.



(c) Capital stocks.



(d) Temperature in degrees celcius above pre-industrial temperature.

Figure 2: Results from the cohort model including demographics after a carbon tax. The dashed lines indicate the baseline trajectories. Green lines indicate green capital in the plots concerned with two types of capital.

4.3 Varying the magnitude of the carbon tax/how much of the stock is fased out [WIP]

The impact on the interest rate from a carbon tax and implied transition, of course, depends on the magnitude of the shift in capital. In the main result, I considered a tax which caused a 30% decrease in the black capital stock and a XX% increase in the green capital stock. In section, I show how the magnitude of the transition impacts the interest rate impacts.

4.4 Changes to the production function [WIP]

When analysing the effects of climate change mitigation, one can consider several types of shocks. Instead of a standard carbon tax, new production ways or standards can alter firms' production possibilities. This could be caused by direct regulation. E.g. rules for how much black capital or energy is allowed or that certain new technologies are now legally required (e.g. cleaner machines). A change in the production function could thus be caused by changing production standards that make green capital relatively more productive and by the government enforced new standards (e.g. requirements of more green capital causing innovation in only one of the capital types).

Depending on the magnitude of this type of shock, the effects are similar to that of a carbon tax. In Figure 3 in Appendix A, I lower α_2 from 0.32 to 0.2 which yield similar results to the carbon tax.

4.5 Results with varying green preferences [WIP]

One could suspect that the individuals' preferences for green capital depend on the relative amounts of capital. For instance, would individuals still accept a lower return on green assets if all assets were suddenly green? This is the same as considering the case where ω_k is a function of k^g and k^b. Consider the case where $\omega_k^{\text{new}} = \omega_k \cdot \frac{k^b}{k^g}$. I assume that individuals take their preferences as exogenously given. I.e. they do not take into account effects of their choices on their preferences. Simulating the model with the new preferences imply higher green interest rates because, as the world becomes greener, individuals do not accept as low green interest payments as before. This also means that the weighted average interest rate is now higher in the new steady state after the green tax. See Figure **??** in Appendix **??**.

4.6 Sensitivity of other individual parameters [WIP]

In this section, I consider sensitivity analysis of individual parameters. Since this is a one-dimensional approach, I cannot rule out that any higher-dimensional combination of parameter changes could result in different results than the sum of the partial analysis. The model is, however, relatively standard and thus, I will rely on one-dimensional sensitivity analysis.

First, consider the production function parameter that were not already discussed. The elasticity of substitution between labour and capital ϵ (equal to 0.8) in baseline, and between green and black capital γ (equal to 2 in baseline) both matter for the quantitative results and one could, in fact, imagine that these were not time-invariant.

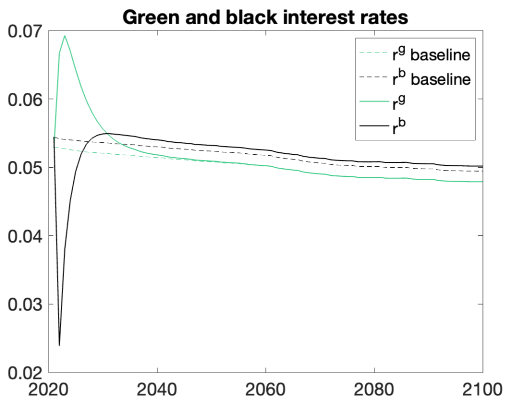
5 Discussion

The real interest rate is important for a number of reasons. It affects central banks' room to conduct monetary policy and it influences individuals' savings behaviour and risk taking. Furthermore, it changes optimal tax policy as presented in Auerbach and Gale (2021). In general, interest rates have been steadily declining for a number of structural reasons - ageing, changes in population and productivity growth etc. The literature on this area is substantial. Climate policy, however, is an additional factor that the scientific community has yet to take into account.

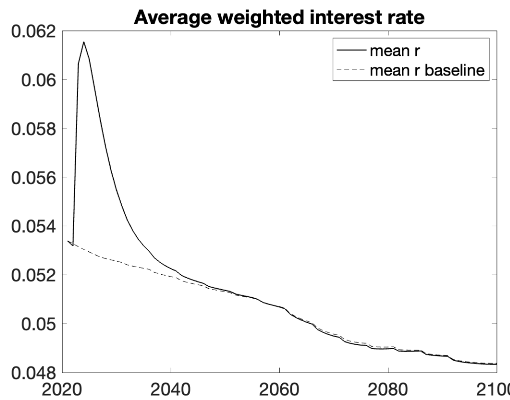
In this paper, I show that the green transition will put an upwards pressure on the real interest rate due to the large capital changes required to restructure production to low-emission world. The increase in the real interest rate caused by the green transition is comparable in magnitude to that of the demographic changes which decreases the interest rate. The effect from climate policy is, however, temporary and the interest rate thus returns to the baseline after the transition.

Importantly, I have not included any risk in the model. Including risk would have introduced another mechanisms through which climate policy would increase the real interest rate. Climate change in itself makes the world a riskier place and increased risk pushes the real interest rate down because of precautionary savings (see Bylund and Jonsson (2020)). Oppositely, policies which effectively mitigate climate change will then alleviate the need for precautionary savings and in turn increase the real interest rate. This channel thus magnifies the mechanisms presented in the current paper.

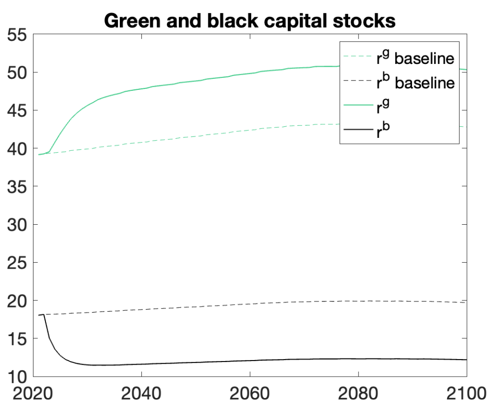
A Appendix results



(a) Green and black interest rates net of depreciation.



(b) The average weighted interest rate net of depreciation.



(c) Capital stocks

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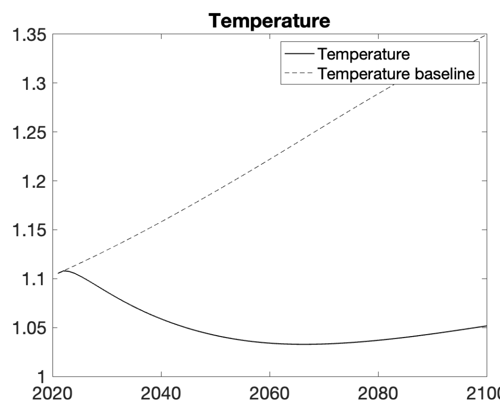

(d) Temperature in degrees celcius above pre-industrial temperature.

Figure 3: Results from the cohort model including demographics. The dashed lines indicate the baseline trajectories. Green lines indicate green capital in the plots concerned with two types of capital.

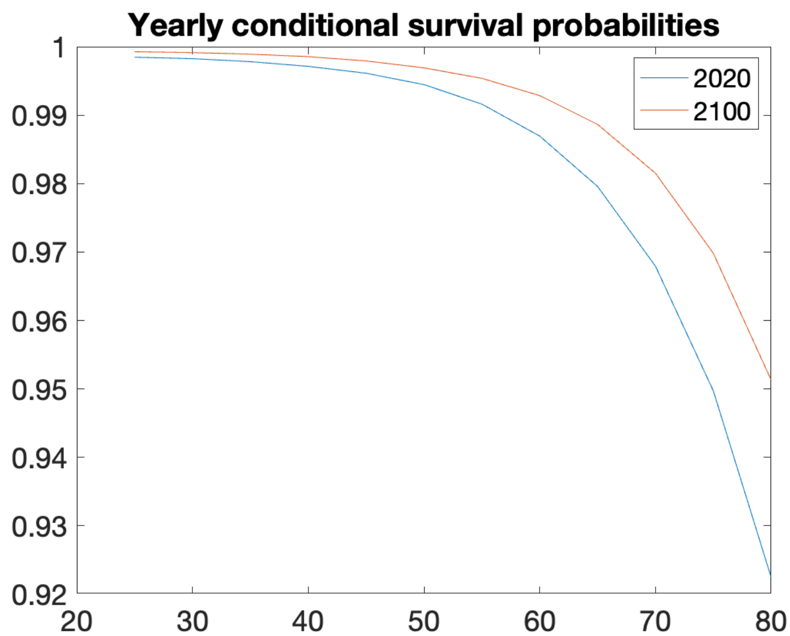

Figure 4: Conditional survival probability now and in 2100 according to the UN population forecast.

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