Staff memo

The impact of the green transition on the neutral interest rate

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Summary

This paper examines how the green transition – implemented by either a carbon tax, green subsidies, or a policy of promoting green preferences – affects the neutral interest rate in a two-sector macroeconomic model with an environmental block. Assuming perfect capital mobility between the sectors, the carbon tax puts downward pressure on the neutral rate during the transition, while there is upward pressure from green subsidies. A policy of green preferences has negligible effects. In the case of imperfect capital mobility, both a carbon tax and green subsidies lead to upward pressure on the neutral rate in the green sector, but downward pressure in the fossil-based sector.

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1 Introduction

Climate change and rising global temperatures are likely to increase the frequency and intensity of extreme weather events, leading to large economic costs and threats to human living conditions. From a central bank perspective, climate change can pose a threat to the core mandates of monetary and financial stability. This is noted in the recent overview of the ECB's monetary policy strategy and in the Basel Committee's strategic priorities.[2] Furthermore, the Network for Greening the Financial System suggests that central banks should improve their knowledge of the potential impact of climate change on the neutral interest rate:[3]

"Central banks would benefit from enhanced assessments of the potential impact on the natural interest rate [from climate change] since that could reveal that policy space is more limited than previously thought, which has implications for the conduct of monetary policy."

The neutral rate plays a special role in monetary policy, serving as a guide for setting the policy rate. This is evident in simple monetary policy rules like the Taylor rule.[4] In the long run, the policy rate should equal the nominal neutral rate (the neutral rate plus the inflation target). In the short run, the rule tells us that the current policy rate, in addition to the nominal neutral rate, should react to deviations of inflation from the target and the output gap. There can, however, be different definitions of the neutral rate. This study follows the New Keynesian literature and defines the neutral rate as the hypothetical real interest rate in an economy without nominal imperfections.[5]

This study investigates how the transition to a greener and more sustainable economy may impact the neutral rate. It is widely recognised that a global carbon tax is the most cost-effective way to limit carbon emissions and, by extension, implement the green transition. This was noted by Nordhaus (1977) in the 1970s, and subsequent studies have confirmed his view.[6]

However, the introduction of carbon taxes has been slow in many countries.[7] To meet the Paris Agreement's goal of limiting global warming to 2°C or below, a more comprehensive approach involving multiple policies is most likely necessary. For instance, the Biden administration emphasised an "all-of-society action" to achieve net-zero emissions by 2050, with policies such as green subsidies and environmental regulations playing notable roles.[8]

We examine three different policies to implement the green transition: a carbon tax, green subsidies, and a policy promoting green preferences. The latter can be viewed as

[2] See ECB (2021) and BIS (2022).

[3] See NGFS (2020). Note that we use the terms "neutral" and "natural" interchangeably, but the two terms are sometimes defined differently, see Platzer et al. (2022).

[4] See Taylor (1993).

[5] See Woodford (2003).

[6] See e.g. Nordhaus (1993) or Golosov et al. (2014).

[7] See Carattini et al. (2018).

[8] See US Executive Office of the President (2021) and the Inflation Reduction Act of 2022.

a regulatory approach that relies on individual responsibility to shift consumption and production patterns towards greener alternatives. In our model, this is represented as an exogenous shift in the firms' production function towards greener goods. This shift could also be interpreted as stemming from various environmental regulations that make it more costly or difficult to use fossil-based resources in production. The pricing of emission rights is not explicitly examined, as it would be similar to a carbon tax in our model.

The analysis is conducted within a two-sector real business cycle model augmented with an environmental block. One sector is green, with emissions aligned with the Paris Agreement's 2°C or below. The other sector is fossil-based, where carbon emissions are a by-product of production. Firms in this sector have access to an emission-abatement technology, though it incurs an economic cost.

Given the central role of the US economy in the global financial system – and its influence on global financial conditions, including interest rates – we calibrate the model to reflect some stylised facts of the US economy.[9] Most importantly, we set the green transition path in line with the median of the latest proposed transition paths for the US goal of achieving net-zero emissions by 2050, as detailed in United States Executive Office of the President (2021).[10]

Summary of the results. In the benchmark simulations, we assume perfect capital mobility, which leads to an equalisation of the neutral rate between the two sectors. The carbon tax puts downward pressure on the neutral rate during the transition. To understand this effect, we decompose the neutral rate into its key determinants. In the green sector, the neutral rate is determined by the marginal product of capital (the labour-to-capital ratio) and the relative price of green goods. The carbon tax encourages firms in this sector to increase capital investment and hire more labour. Capital accumulation is a slow process while labour can increase more quickly. These effects raise the marginal product of green capital. However, this is counteracted by a larger decrease of the relative price of green goods, leading to a decline in the neutral rate in the green sector.

In the fossil-based sector, the marginal product of fossil-based capital and the relative price of fossil-based goods both rise. These effects are, however, outweighed by a larger negative impact on the neutral rate from higher abatement efforts and emission costs. As a result, the neutral rate in both sectors falls by just over 0.7 percentage points during the transition.

The revenue from the carbon tax is used as lump-sum transfers to households in this benchmark case. In the sensitivity analysis, we examine the effects of using the revenue instead to subsidise either capital or labour in the green sector. This encourages further emissions reductions compared to the benchmark, but the effect is quantitatively small. The reasons are twofold: first, the revenue from the carbon tax is relatively small, and second, green subsidies are less effective and more costly in terms of reducing

[9] See Boehm and Kroner (2023).

[10] This strategy was revoked by the Trump administration in 2025, but since no new strategy has yet been presented, we use the transition paths as outlined in United States Executive Office of the President (2021).

emissions than the carbon tax. There are non-negligible effects on certain economic variables, but the impact on the neutral rate is not sensitive to how the carbon tax revenue is used in the model.

The effectiveness of a carbon tax depends on the substitution elasticity between green and fossil-based goods. A lower substitution elasticity reduces the tax's effectiveness, as the cost of shifting production from fossil-based to green goods becomes higher, and the price changes therefore have smaller effects on quantities. Aggregate variables are largely unaffected, though, and the neutral rate shows little sensitivity to changes in the substitution elasticity.

A subsidy to green firms puts upward pressure on the neutral rate. This is due to the subsidy itself that pushes the green neutral rate upwards. This effect is partially offset by a lower relative price of green goods and a falling marginal product of capital resulting from large investments in green capital. In the fossil-based sector, the higher price of fossil-based goods pushes the fossil-based neutral rate upward, though a lower marginal product of fossil-based capital somewhat mitigates this effect. The neutral rate increases by at most a bit over 1 percentage point during the transition.

In the case of imperfect capital mobility between the sectors, the neutral rates in the green and fossil-based sectors are not equalised. The carbon tax causes an increase of the green neutral rate during the transition, while the neutral rate in the fossil-based sector decreases. The results of a subsidy to green firms are similar, i.e., the neutral rate in the green sector rises, while the fossil-based neutral rate initially falls but increases in later periods of the transition.

The policy of promoting green preferences is by assumption driven by an exogenous increase of production of green goods. There are thus no price incentives to change behaviour. This policy causes large sectoral reallocations of output, capital, and labour toward the green sector. However, the effects on aggregate variables are minimal, meaning the neutral rate remains essentially unaffected during the transition.

Related literature. The economic risks of climate change are often divided into physical and transition risks. Jørgensen (2024) examines how the green transition implemented by a carbon tax affects the neutral rate in an overlapping generations model with two kinds of capital: non-emitting green capital and emitting capital. The results show that the neutral rate increases during the transition, driven mainly by higher demand for green capital. Jézéquel-Royer and Levieuge (2024) assesses the impact of an orderly environmental transition on the Euro area natural rate of interest using high-frequency identification methods, isolating carbon policy shocks from EU ETS futures price variations around regulatory announcements. They find a significant and persistent increase in the natural rate following a positive carbon policy shock. Mehrotra (2025) examines the implications of transitioning to net-zero emissions. A net zero target operates as both an anticipated negative productivity shock and a negative capital shock. For monetary policy this is a negative aggregate demand shock that lowers the natural rate of interest.

Bylund and Jonsson (2020) examine how physical risks – in terms of weaker growth, higher uncertainty, and higher risks of disasters – affect the long run neutral rate. Their results indicate that under certain conditions the long run rate can decline significantly. Ojeda-Joya (2022) presents a counterfactual analysis to estimate the potential effect of global warming on the neutral rate using a state-space semi-structural model of inflation and output determination. The counterfactual shows a clear decline of the neutral rate. Casey et al. (2024) use the neoclassical growth model to analyse how climate policies affect the long-run real interest rate. They show that a carbon tax reduces the long-run interest rate, while energy subsidies may work in the opposite direction.

Levine and Pontines (2024) do not evaluate climate policies per se but show how climate-induced temporary supply disruptions affect the neutral rate. They find that following a negative supply shock, the decrease in the neutral rate is accentuated when environmental damage is accounted for, and if the estimate of the current stock of carbon dioxide in the atmosphere doubled, the impact would become even more pronounced. Finally, Mongelli et al. (2022) provide a literature survey on climate change and the neutral rate. One of their conclusions is that the long-run effect of climate change on the real interest rate can be substantial, particularly in scenarios where trend growth falls due to reduced productivity or due to serious climate-related physical damages.

The rest of the paper is organised as follows. In the next section we discuss different ways to implement the green transition. Section 3 presents the model and calibration. The benchmark results are presented in section 4, while section 5 provides sensitivity analysis. Section 6 concludes with some suggestions for future research.

2 Implementing the green transition

Climate change is an example of a negative externality or market failure.[11] When households and firms make decisions about carbon emissions, they typically consider only their own costs, ignoring the broader societal costs. This leads to excessive emissions from a societal perspective. A cost-effective solution to address this externality is a Pigouvian tax, see Pigou (1920). The aim of this tax is to ensure that households and firms internalise the societal costs in their decision-making.

The carbon tax is an example of a Pigouvian tax, designed to ensure that the firms' cost of emitting carbon dioxide equals the societal cost. Additionally, it encourages firms to adopt more efficient and environmentally friendly technologies. Unlike other taxes, such as those on labour or capital, whose main purpose is to generate government revenue, the goal of a carbon tax (and Pigouvian taxes in general) is to correct market failures.

Green subsidies are increasingly used as an alternative to carbon taxes to mitigate carbon emissions. For example, the 2022 US Inflation Reduction Act allocates 369 billion USD in green subsidies and tax credits over the next decade. The appeal of green subsidies over carbon taxes is often political: unlike a carbon tax, which raises the cost of carbon-intensive goods, green subsidies reduce the cost of producing low-carbon goods, which may pose less immediate threat to output. Green subsidies also

[11] The Stern Review from 2007 described climate change as “the greatest market failure the world has ever seen”, see Stern (2007).

incentivise advancements in green technologies and improve domestic energy security, especially for countries reliant on fossil fuels.

However, the economic impact of green subsidies depends on their design and financing. For instance, the effects of a subsidy for green investments can be different to those of a general subsidy for green production. Additionally, how the subsidy is financed matters: the impact of capital taxation on the economy differs from the impact of labour taxation.[12]

While carbon taxes and green subsidies are market-based policies, a policy of promoting green preferences reflects a non-market approach. Shifting household and firm preferences toward greener choices can be a part of the green transition, see NGFS (2024a). It is reasonable to think that consumption choices reflect both prices and values, with some households intrinsically caring about the environment, see Besley and Persson (2023). As the effects of climate change become more apparent, both households and firms are increasingly likely to express “green preferences” in their decisions.

3 Model

We examine the effect of the green transition on the neutral rate within a two-sector real business cycle model, incorporating an environmental block inspired by Heutel (2012) and Annicchiarico and Di Dio (2015). Production occurs in both a green sector and a fossil-based sector, with capital and labour as factor inputs in each. Firms in the green sector follow a carbon emission policy consistent with the Paris Agreement, aiming for a temperature rise of 2°C or below. Emissions in the fossil-based sector are a by-product of production, but firms have access to an abatement technology that can reduce emissions at a cost.

Green and fossil-based goods are aggregated into a final good using a constant elasticity of substitution function. This final good is then used for consumption and investment. Households derive utility from consumption and experience disutility from labour. They work in both sectors and save in the capital stock.

3.1 Households

The representative household has a utility function $\mathcal{U}$, which includes consumption C and hours worked H, over an infinite horizon,

$$\sum_{t=0}^{\infty} \beta^t \mathcal{U}(C_t, H_t),$$

where β is a subjective discount factor of current and future utility. Households save by investing in the physical capital stock K, which evolves according to the following law of motion,

[12] See Kalkuhl et al. (2013), Metcalf (2009), and Newell, Pizer and Raimi (2019) for further discussions of the pros and cons of green subsidies.

$$K_t = I_t + (1-\delta)K_{t-1}$$

where I is investments and δ is the depreciation rate of capital. The representative household maximises utility subject to the following intertemporal budget constraint,

$$C_t + I_t = r_t K_{t-1} + w_t H_t + T_t,$$

where r is the rental rate of capital or the neutral rate for short, w the wage rate, and T can be a lump-sum government transfer or a lump-sum tax. The first order conditions are summarised as follows,

$$\mathcal{U}'_{C_{t,t}} = \big(r_{t+1} + (1-\delta)\big)\beta\mathcal{U}'_{C_{t,t+1}},$$

$$w_t\mathcal{U}'_{C_{t,t}} = -\mathcal{U}'_{H_{t,t}},$$

The first condition ensures that the marginal cost of an extra unit of savings equals the marginal benefit. The second condition ensures that the marginal cost of an extra unit of hours worked equals the marginal benefit.

3.2 Firms

Production takes place in two intermediate production sectors: an environmentally friendly green sector and a fossil-based sector. Firms in both sectors produce intermediate goods under perfect competition. In the fossil-based sector, firms combine capital and labour to produce intermediate goods Y^F,

$$Y_t^F = \mathcal{F}(D_t, K_t^F, H_t^F),$$

where the superscript F indicates the fossil-based sector variables and D is a damage function.[13] Carbon emissions are a by-product of production in this sector and cause damage to production in both sectors. The damage function is a quadratic function of the stock of carbon in the atmosphere S,

$$D_t = \delta_0 + \delta_1 S_t + \delta_2 S_t^2,$$

where the parameters δ_0, δ_1, and δ_2 determine the strength of the damaging effect of carbon emissions. Profit-maximising firms do not take the damage from carbon emissions into account, which causes the negative externality. The stock of carbon emissions is a function of domestic emissions Z and exogenous rest-of-the-world emissions Z^*, according to the following law of motion,

$$S_t = \delta_S S_{t-1} + Z_t + Z^*,$$

where δ_S is the decay rate of the stock of carbon. Domestic emissions are an increasing function of output in the fossil-based sector and a decreasing function of the firm's abatement effort U. This function is labelled $\mathcal{M}$,

[13] We use $\mathcal{F}$ to describe a general production function. The actual function is described in the calibration section.

$$Z_t = \mathcal{M}(Y_t^F, U_t).$$

A carbon tax τ^E is imposed on domestic emissions to encourage firms in the fossil-based sector to abate emissions. Total abatement spending A is represented by a function $\mathcal{A}$, which is increasing in the abatement effort and the output in the fossil-based sector,

$$A_t = \mathcal{A}(Y_t^F, U_t).$$

Firms in the fossil-based sector maximise profits subject to the cost of labour, the rental cost of capital, the cost of the carbon tax, and the cost of total abatement spending. The first order conditions can be summarised as follows,

$$r_t = \mathcal{F}'_{K_t^F}\left(p_t^F - \tau_t^E \mathcal{M}'_{K_{t,t}^F} - \mathcal{A}'_{K_{t,t}^F}\right),$$

$$w_t = \mathcal{F}'_{H_t^F}\left(p_t^F - \tau_t^E \mathcal{M}'_{K_{t,t}^F} - \mathcal{A}'_{K_{t,t}^F}\right),$$

$$\tau_t^E \mathcal{M}'_{U_{t,t}} + \mathcal{A}'_{U_{t,t}} = 0,$$

where p^F is the price of the fossil firm's output in terms of the price of the consumption good. The first condition ensures that the marginal cost of an extra unit of capital equals the marginal benefit, which takes the marginal cost of emissions and the marginal cost of abating emissions into account. The second condition ensures that the marginal cost of an extra unit of labour equals the marginal benefit, which also takes the marginal cost of emissions and the marginal cost of abating emissions into account. The third condition ensures that the marginal cost of an extra unit of effort to abate emissions equals the marginal benefit.

Firms in the green sector combine capital and labour to produce green intermediate goods,

$$Y_t^G = (1 + \varsigma_t^Y)\mathcal{F}(D_t, K_t^G, H_t^G) + \varsigma_t^K K_t^G + \varsigma_t^H H_t^G,$$

where the superscript G indicates green sector variables, ς^Y is a general subsidy to production, ς^K is a subsidy to capital, and ς^H is a subsidy to labour. Depending on the case under consideration, the subsidies can be either positive or zero. Firms maximise profits subject to the rental cost of capital and the cost of labour. They take potential subsidies as given. The first order conditions are given by,

$$r_t = (1 + \varsigma_t^Y) p_t^G \mathcal{F}'_{K_t^G} + \varsigma_t^K,$$

$$w_t = (1 + \varsigma_t^Y) p_t^G \mathcal{F}'_{H_t^G} + \varsigma_t^H,$$

where p^G is the price of the green firm's output in terms of the price of the consumption good. The first condition equalises the marginal cost of an extra unit of capital to the marginal benefit, which may include a general subsidy or a capital subsidy, while the second condition equalises the marginal cost of an extra unit of labour to the marginal benefit, which may include a general subsidy or a labour subsidy.

The aggregated final good Y is defined by a standard constant elasticity substitution function over the green and fossil intermediate goods,

$$Y_t = \left[(\omega_y)^{\frac{1}{\eta_y}} (Y_t^G)^{\frac{\eta_y - 1}{\eta_y}} + (1 - \omega_y)^{\frac{1}{\eta_y}} (Y_t^F)^{\frac{\eta_y - 1}{\eta_y}} \right]^{\frac{\eta_y}{\eta_y - 1}},$$

where the parameter ω_y is the weight on the green good and the parameter η_y is the elasticity of substitution between the green and fossil intermediate goods.

3.3 Government

The government may obtain revenue from a carbon tax or a lump-sum tax and depending on the scenario the revenue is used as:

- A lump-sum transfer to households
- A subsidy to firms in the green sector
- A subsidy to capital in green sector
- A subsidy to labour in the green sector

The government budget constraint is given by,

$$T_t = \tau_t^E \mathcal{M}(Y_t^F, U_t) - \varsigma_t^Y p_t^G Y_t^G - \varsigma_t^K K_t^G - \varsigma_t^H H_t^G.$$

When the income from the carbon tax is used as a lump-sum transfer to households, the subsidies are thus set to zero,

$$\varsigma_t^Y = \varsigma_t^K = \varsigma_t^H = 0.$$

When the green transition is implemented by a subsidy to firms in the green sector, the subsidy is financed by a lump-sum tax. The carbon tax and the subsidies to green capital and labour are thus zero,

$$\tau_t^E = \varsigma_t^K = \varsigma_t^H = 0.$$

In the sensitivity analysis, we examine the effects of using the revenue from the carbon tax as either a subsidy to green capital or green labour. In the case of a subsidy to green capital, the following holds,

$$T_t = \varsigma_t^Y = \varsigma_t^H = 0,$$

and in the case of a subsidy to labour, the following holds,

$$T_t = \varsigma_t^Y = \varsigma_t^K = 0.$$

3.4 Market clearing

To ensure that supply and demand are equal in all markets and that the resource constraint is fulfilled, the following conditions hold in equilibrium,

$$K_{t-1} = K_t^G + K_t^F,$$

$$H_t = H_t^G + H_t^F,$$

$$Y_t = C_t + I_t + A_t.$$

3.5 Calibration and functional forms

The model is calibrated to some stylised facts of the US economy. The parameter values used in the simulations are summarised in Table 1. The length of a period is one quarter. The depreciation rate δ is set to its standard value 0.025, which together with a discount factor β of 0.985 implies an investment to output ratio of about 20 per cent in steady state and an annual investment to capital ratio of 10 per cent. Both values are in line with US data, see Reis (2021).

The period utility function takes the following functional form,

$$\mathcal{U}(C_t, H_t) = \frac{(C_t - \varphi C_{t-1})^{(1-1/\sigma)}}{1 - 1/\sigma} - \frac{H_t^{(1+1/\eta)}}{1 + 1/\eta},$$

where σ is the intertemporal elasticity of substitution, φ is the measure of external habit formation, and η is the Frisch elasticity of labour supply. We set σ equal to 0.5, which is the mean elasticity in a meta-analysis of 169 published studies, see Havranek et al. (2015). The habit parameter φ is set to 0.7 as in Smets and Wouters (2007). Estimates in Domeij and Flodén (2006) suggest that the Frisch elasticity is in the range of 0 to 0.5. We set the Frisch elasticity to 0.5.

The calibration of the environmental block follows Annicchiarico and Di Dio (2015). The emission cost function is of the following form,

$$\mathcal{A}(Y_t^F, U_t) = \mu_1 (U_t)^{\mu_2} Y_t^F,$$

where the parameter μ_1 is set to 0.185 and the curvature parameter μ_2 to 2.8. The functional form of the domestic emissions is given by,

$$\mathcal{M}(Y_t^F, U_t) = \gamma(1 - U_t) Y_t^F,$$

where the parameter γ is set to 0.47, which ensures that the US carbon emissions are 5.06 $GtCO_2$, see Global Carbon Budget (2023). The global emissions of carbon in 2022 were 37.15 $GtCO_2$ on a yearly basis, see Global Carbon Budget (2023). This implies that Z^* must be 32.09/4 $GtCO_2$ each quarter. The decay rate δ_S in the law of motion for carbon is set to 0.99475 to ensure that the global stock of carbon is 1770 $GtCO_2$, see Global Carbon Budget (2023). Finally, the parameters δ_0, δ_1, and δ_2 are set to 1.395e-3, −6.6722e-6, and 1.4647e-8, respectively, see Annicchiarico and Di Dio (2015).

The production function in the green sector has the following functional form,

$$\mathcal{F}(D_t, K_t^G, H_t^G) = (1 - D_t)(K_t^G)^{\theta_g} (H_t^G)^{(1-\theta_g)},$$

and in the fossil-based sector it has the following functional form,

$$\mathcal{F}(D_t, K_t^F, H_t^F) = (1 - D_t)(K_t^F)^{\theta_f} (H_t^F)^{(1-\theta_f)}.$$

The elasticity of output with respect to capital in the green sector $\theta_g$and in the fossil-based sector θ_f are both set to the standard value of 0.33. The capital income to GDP ratio then becomes 33 per cent, which is slightly higher than the 26 to 29 per cent observed in the data, see Reis (2021).

Table 1. Parameter values

Parameter	Description	Value
β	Discount factor	0.985
σ	Intertemporal elasticity of substitution	0.5
η	Frisch elasticity	0.5
δ	Depreciation rate of capital	0.025
φ	Habit formation	0.7
δ_0	Damage function parameter	1.395×10^{-3}
δ_1	Damage function parameter	-6.6722×10^{-6}
δ_2	Damage function parameter	1.4647×10^{-8}
δ_s	Decay rate of carbon	0.99475
E^*	Rest-of-the-world emissions	32.09/4
μ_1	Abatement cost shift parameter	0.185
μ_2	Abatement cost curvature parameter	2.8
γ	Shift parameter in domestic emission function	0.47
θ_g	Elasticity of output with respect to capital in the green sector	0.33
θ_f	Elasticity of output with respect to capital in the fossil-based sector	0.33
ω_y	Weight on green output	0.3
η_y	Substitution elasticity between green and fossil-based goods	5
κ	Capital adjustment cost in the green sector	5 to 50

Firms are classified as green if they have an emission policy in line with the Paris Agreement of 2°C or below. To calibrate the share of green firms, we use sectoral data from the Transition Pathway Initiative, according to which about 30 per cent of all firms have an understanding of risks and opportunities related to the low-carbon transition and integrate this into their business strategy and capital expenditure decisions.[14] Hence, the weight on green output in the CES production function is set to 0.3. The price

[14] See https://www.transitionpathwayinitiative.org/tpi/sectors.

elasticity between green and fossil-based goods is set to 5, see Benmir and Roman (2020). Finally, in the sensitivity analysis where we assume imperfect capital mobility, we vary the capital adjustment parameter in the green sector from 5 to 50.

4 Benchmark results

The US net-zero goal of carbon emissions in 2050 involves both emission reductions and carbon removals. Therefore, the actual emissions will not be zero in 2050. The proposed median emission path asserts 3 $GtCO_2$ in 2030, 2 $GtCO_2$ in 2040, and 0.75 $GtCO_2$ in 2050, see United States Executive Office of the President (2021). The starting value in our simulations is set to the 2022 level of 5 $GtCO_2$, see Global Carbon Budget (2023). Figure 1 shows the emission path.

Figure 1 also shows the transition paths for the carbon tax, the green subsidy, and the policy of green preferences (the share of green goods in production) that each fulfil the net-zero goal. To implement the green transition through a carbon tax, a tax rate of 0.72 is required by 2050, which corresponds to approximately 3.6 per cent of GDP. In this benchmark case, government revenue from the carbon tax is transferred to households. In the sensitivity analysis, we explore how the results change when this revenue is instead used as subsidies for either capital or labour in the green sector.

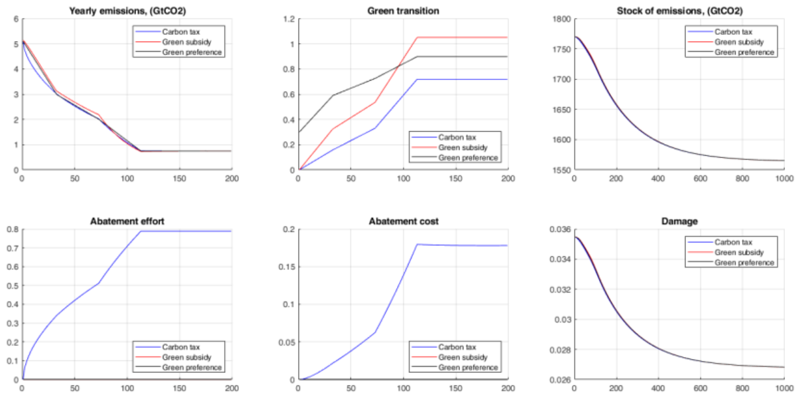
To achieve the green transition solely through a green subsidy, a subsidy of slightly above 1 is necessary by 2050 to reach net-zero emissions. The cost of this subsidy is equivalent to a lump-sum tax of over 90 per cent of GDP, suggesting that a policy of green subsidies is significantly less cost-effective than a carbon tax. The main reason for this is that green subsidies do not incentivise firms in the fossil-based sector to reduce carbon emissions, as a carbon tax does. Moreover, the cost of the subsidy is likely underestimated, since lump-sum taxation is generally not feasible in most countries. Had the green subsidy been financed more realistically through proportional labour or capital taxes, the welfare cost would have been very high. This is especially true if the cumulative welfare cost of the tax distortions also accounts for imperfect competition in product and labour markets, as discussed by Jonsson (2007).

A policy of green preferences requires increasing the share of green goods in production from the current 30 per cent to around 90 per cent. Like green subsidies, this policy does not encourage fossil-based firms to reduce emissions. Therefore, a large production shift toward the green sector is necessary to meet the net-zero goal.

The decay of carbon emissions in the atmosphere is a slow process. To reach the new and lower stock of carbon emissions takes more than 250 years. The damage to production in the model is solely dependent on the stock of emissions, making it a long-lasting process as well.

The carbon tax encourages firms in the fossil-based sector to increase their efforts to abate carbon emissions. The level of this effort depends directly on the tax and increases as the tax rises. The cost of emissions depends not only on abatement efforts but also on output in the fossil-based sector. This creates two counteracting effects. On the one hand, increasing abatement efforts pushes costs upwards. On the other hand, reduced fossil-based production drives costs down. The former effect dominates, and as a result, the abatement cost increases.

Figure 1. Effects on environmental variables of a carbon tax, a subsidy to green firms, and a policy of green preferences



Note: Damage, abatement effort and abatement cost are in output units.

Figure 2 shows the economic implications of the green transition. Most variables are permanently affected, with two notable exceptions. First, the neutral rate remains unaffected in the long run, as it is determined by the household's discount factor in steady state. Second, there are no lasting price effects from the policy of green preferences, and only minimal effects on aggregate variables. By assumption, households increase their consumption of green goods without any price incentives.

The primary effect of the carbon tax is to increase the cost of fossil-based goods, making green goods relatively cheaper. This leads to a rise in the demand for green goods. To meet this demand, green firms hire more labour and invest more in capital. Meanwhile, the demand for fossil-based goods declines, prompting firms in this sector to reduce their use of input factors.

While the production of green goods increases, the output of fossil-based goods decreases. Given that fossil-based goods account for 70 per cent of the final goods production, overall output declines. This reduction in aggregate output translates into lower income, which subsequently reduces consumption and investment.

Perfect labour mobility ensures wage equality between sectors. To understand the decline in wages, consider how the carbon tax influences the marginal rate of substitution between labour and consumption. As consumption falls, the marginal utility of consumption rises, while the disutility of labour remains largely unchanged, since total hours worked are almost unaffected. As a result, the marginal rate of substitution decreases, putting downward pressure on wages. The neutral rate also decreases during the transition, by at most 5 per cent. The next sub-section provides a decomposition of the principal forces explaining this outcome.

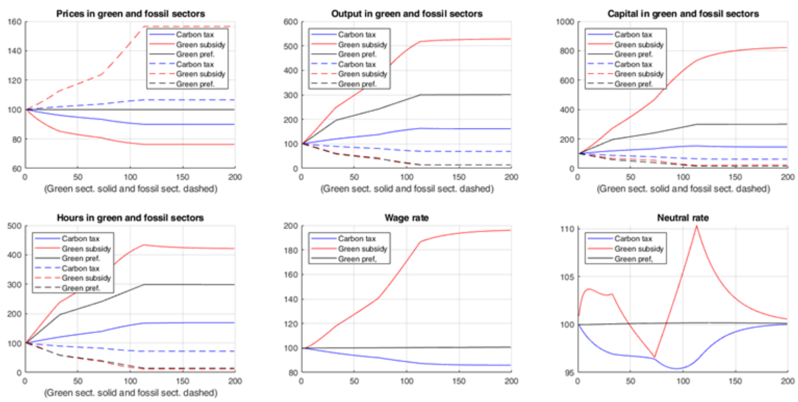
The green subsidy, like the carbon tax, makes green goods relatively cheaper. Households increase their demand for green goods at the expense of fossil-based ones.

However, unlike the carbon tax, the green subsidy does not incentivise fossil-based firms to reduce emissions. Emission reductions occur solely through an increase in green goods production and a decrease in fossil-based goods production. This transition requires significant relative price adjustments: the price of green goods must fall by around 30 per cent, while fossil-based goods become about 60 per cent more expensive.

The significant growth in green goods production leads to an increase in aggregate output. Additionally, both labour and capital demand rise, along with wages. The disutility of labour increases, and since the marginal utility of consumption remains largely constant, this puts downward pressure on the marginal rate of substitution.[15] The neutral rate fluctuates irregularly, varying between –4 and 10 per cent, before returning to its long-run value. The next sub-section explores the main factors behind this outcome.

The policy of green preferences is assumed to be driven by changes in quantities without any price incentives. To reach the net-zero goal by 2050, the production of green goods must increase by about 300 per cent, while fossil-based goods must decrease by over 80 per cent. Although these shifts result in significant sectorial re-allocations, the effects on aggregate variables remain small. As a result, both the wage rate and the neutral rate remain largely unaffected.

Figure 2. Effects on economic variables of a carbon tax, a subsidy to green firms, and a policy of green preferences



Note: The variables are normalised by the initial steady state and multiplied by 100.

4.1 Decomposing the effects on the neutral rate

Perfect capital mobility leads to an equalisation of the neutral rate between the two sectors. To understand the neutral rate's transition path, we decompose the neutral

[15] While the increase in output, hours worked, and wages may make green subsidies appear attractive to policymakers and may explain why the introduction of carbon taxes has been slow in many countries, the welfare cost of green subsidies could still be higher than that of carbon taxation.

rate into its key determinants. We first examine the impact of the carbon tax on the neutral rate and then of a subsidy to firms in the green sector.

A carbon tax. The key determinants of the green neutral rate are given by the first order condition,

$$r_t^G = p_t^G \mathcal{F}'_{K_t^G}.$$

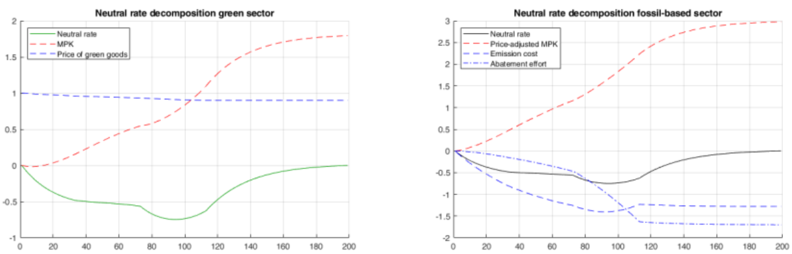
The green neutral rate is thus determined by the marginal product of green capital multiplied by the price of green goods or the "price-adjusted" marginal product of green capital. Figure 3 shows the green neutral rate and the decomposition. The carbon tax encourages green firms to increase capital investment and hire more labour. Capital accumulation is a slow process and labour increases more quickly, which raises the marginal product of green capital. However, this effect is counteracted by a larger decrease in the relative price of green goods, leading to a decline in the neutral rate in the green sector. The green neutral rate falls by at most just over 0.7 percentage points during the transition.

The fossil-based neutral rate is decomposed into the following factors,

$$r_t^F = p_t^F \mathcal{F}'_{K_t^F} - \tau_t^E \mathcal{M}'_{K_{t,t}^F} \mathcal{F}'_{K_t^F} - \mathcal{A}'_{K_{t,t}^F} \mathcal{F}'_{K_t^F}.$$

Figure 3 shows the decomposition in terms of these factors, i.e., the price-adjusted marginal product of fossil-based capital, the abatement effort multiplied by the carbon tax and marginal product of fossil-based capital, and the cost of emissions multiplied by the marginal product of fossil-based capital. The marginal product of fossil-based capital and the relative price of fossil-based goods both rise, implying that the price-adjusted marginal product of fossil-based capital rises. This effect is, however, outweighed by a larger negative impact on the neutral rate from higher abatement efforts and emission costs. As a result, the fossil-based neutral rate also falls by just over 0.7 percentage points.

Figure 3. Neutral rate decomposition – a carbon tax



Note: The variables, except the relative price, are deviations from steady state.

A subsidy to firms in the green sector. The decomposition of the neutral rate given a green subsidy to firms is shown in Figure 4. The green neutral rate is determined by the price-adjusted marginal product of green capital plus the green subsidy multiplied with the price of green goods and the marginal product of green capital,

$$r_t^G = p_t^G \mathcal{F}'_{K_t^G} + \varsigma_t^Y p_t^G \mathcal{F}'_{K_t^G}.$$

The subsidy to green firms puts upward pressure on the neutral rate. This is due to the subsidy itself, but this is partially offset by a lower relative price of green goods and a falling marginal product of green capital resulting from large investments in green capital. The green neutral rate increases by at most a bit over 1 percentage point during the transition.

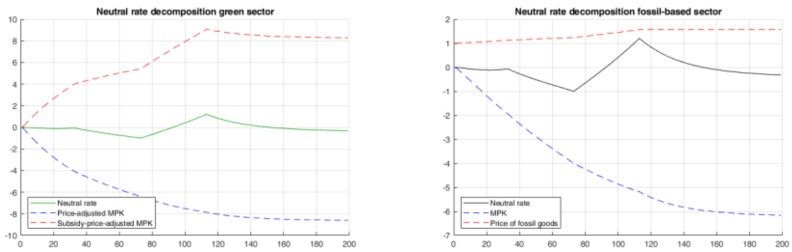
The neutral rate in the fossil-based sector is given by the price-adjusted marginal product of capital,

$$r_t^F = p_t^F \mathcal{F}'_{K_t^F}.$$

The higher price of fossil-based goods pushes the neutral rate upward, but a lower marginal product of fossil-based capital somewhat mitigates this effect. Taking both effects into account, the fossil-based neutral rate increases by at most a bit over 1 percentage point during the transition.

A notable feature of the neutral rate's transition path is the irregular pattern with both decreases and increases. This pattern comes from the irregular transition path of the green subsidy, which has a particularly large impact on the green neutral rate due to the unrealistically large subsidy necessary to implement the net-zero goal.

Figure 4. Neutral rate decomposition – a green subsidy to firms



Note: The variables except for the relative price are deviations from steady state.

5 Sensitivity analysis

This section provides sensitivity analysis with respect to:

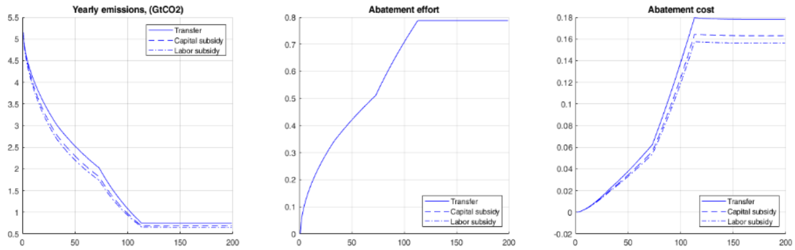
- How the revenue from the carbon tax is used
- The substitution elasticity between green and fossil-based goods
- A faster and smoother green transition
- Imperfect capital mobility

5.1 Using the carbon tax revenue to subsidise green capital or labour

In the benchmark case, the revenue from the carbon tax is distributed as lump-sum transfers to households. In this sensitivity analysis, we explore how the neutral rate is affected when the revenue is instead used to subsidise either capital or labour in the green sector. Intuitively, this should encourage further emission reductions. While this is indeed the case, the effect is quantitatively small. Yearly emissions with green subsidies are only slightly lower than with lump-sum transfers, as shown in Figure 5. This modest effect is due to two factors: (i) the revenue from the carbon tax is relatively small, accounting for only about 3.6 per cent of GDP, and (ii) a policy of green subsidies is relatively costly in terms of emission reduction.

The overall abatement effort remains unaffected by how the government allocates the revenue from the carbon tax, since the effort only depends on the carbon tax itself. However, the cost of emissions depends not only on the abatement effort, but also on output from the fossil-based sector. Compared to lump-sum transfers, the emission cost is slightly lower when the revenue is used for subsidies. This is because subsidies to either green capital or labour reduce fossil-based output somewhat more than lump-sum transfers.

Figure 5. Environmental variables: Carbon tax revenue used for green subsidies



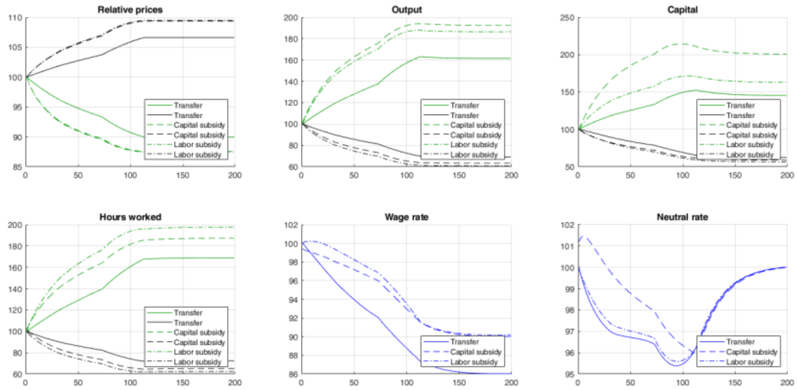
Note: The variables are normalised by the initial steady state and multiplied by 100.

The economic effects are illustrated in Figure 6. Compared to lump-sum transfers, there is a further reduction in the price of green goods and a further increase in the price of fossil-based goods. A property of the Cobb-Douglas production function is that capital and labour are complements. As a result, a subsidy to green capital increases the demand not only for green capital but also for green labour. Similarly, a subsidy to green labour increases the demand for both labour and capital in the green sector. Hence, subsidies to green capital, green labour, or a general subsidy to green firms, as in the benchmark case, will not have very different effects on emissions, at least if capital and labour are complements in production.

Green subsidies lead to a larger increase in production than lump-sum transfers. Unlike lump-sum transfers, green subsidies encourage firms to make additional investments in capital and hire more labour. As a result, the aggregate wage rate increases, driven by a higher disutility of labour due to the rising aggregate labour supply.

The capital subsidy results in a slightly higher neutral rate compared to the labour subsidy and lump-sum transfers. In the green sector, the capital subsidy puts significant upward pressure on the neutral rate. However, this is counteracted by a decreasing marginal product of green capital and lower prices of green goods. In the fossil-based sector, the price-adjusted marginal product of fossil-based capital increases slightly with a green capital subsidy.

Figure 6. Economic variables: Carbon tax revenue used for green subsidies



Note: The variables are normalised by the initial steady state and multiplied by 100.

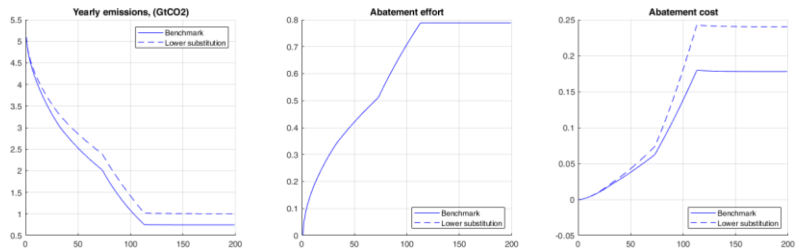
5.2 Lower substitution elasticity

This sub-section examines how a lower substitution elasticity between green and fossil-based goods impacts the neutral rate, compared to the benchmark case. We consider a case in which the substitution elasticity is reduced from the benchmark value of 5 to 0.5. The transition path for the carbon tax is kept the same as in the benchmark case.

A lower substitution elasticity makes final goods firms less responsive to changes in the prices of green and fossil-based goods. As a result, the carbon tax becomes less effective in reducing emissions by shifting production from fossil-based goods to green goods. Consequently, the net-zero emission target of 0.75 $GtCO_2$ is not met, as shown in Figure 7. To achieve the net-zero goal with a lower substitution elasticity, a higher carbon tax would be required.

While the lower substitution elasticity does not directly affect the abatement effort – since the carbon tax follows the same path as in the benchmark case – there are notable consequences. Higher output in the fossil-based sector results in significantly higher cost of emissions compared to the benchmark case.

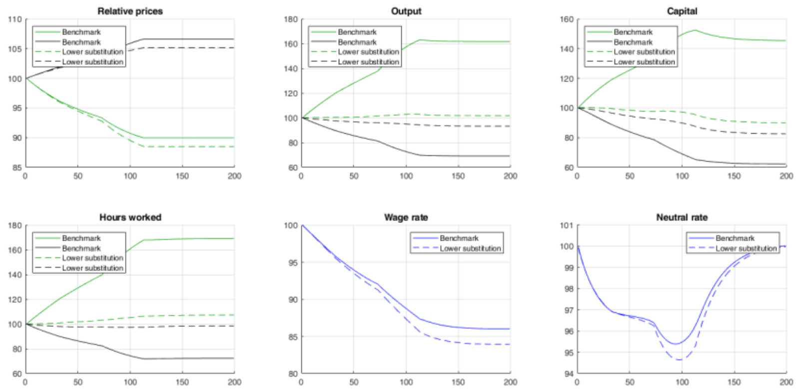
Figure 7. Environmental variables – lower substitution elasticity



Note: The abatement effort and cost are in output units.

The lower substitution elasticity also means that price changes have smaller impacts on sector-specific variables, as illustrated in Figure 8. Capital and hours worked in both sectors are minimally affected by price changes. Since output in both sectors depends on capital and hours worked, it is similarly unaffected. The transition paths for aggregate variables are generally like those in the benchmark case. The wage rate is slightly lower, and the neutral rate experiences a marginally larger decline.

Figure 8. Economic variables – lower substitution elasticity

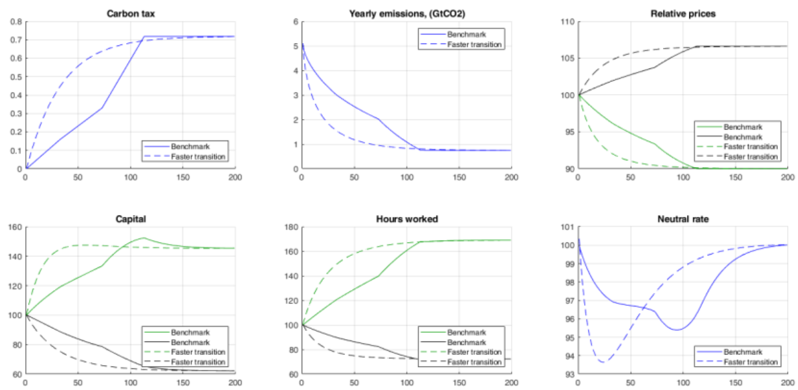


Note: The variables are normalised by the initial steady state and multiplied by 100.

5.3 Faster and smoother transition

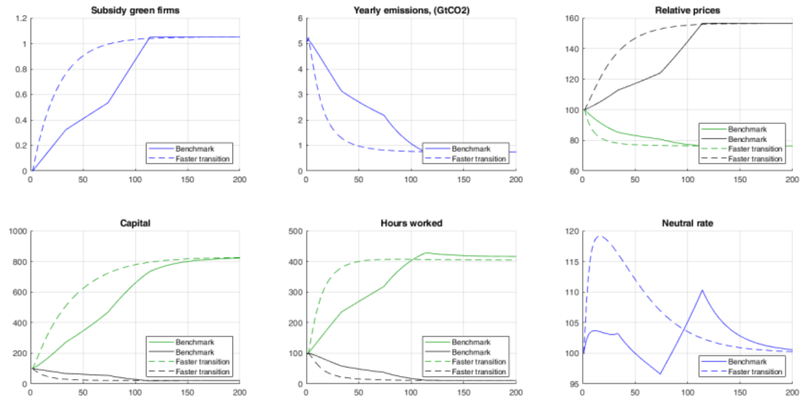
In this sub-section, we examine the impact of a faster and smoother transition path, in which the net-zero goal is reached within approximately 15-20 years. Qualitatively, the mechanisms are similar to those in the benchmark case. However, the carbon tax and green subsidy to firms increase at a faster rate initially, resulting in more pronounced effects at the outset, as shown in Figures 9 and 10 for the carbon tax and the subsidy to green firms, respectively. The fall in the neutral rate due to the carbon tax is larger and occurs earlier in the transition. Similarly, the rise in the neutral rate from the green subsidy is more significant and happens earlier than in the benchmark case.

Figure 9. Faster and smoother transition – a carbon tax



Note: The relative prices, capital, hours worked, and the neutral rate are normalised by the initial steady state and multiplied by 100.

Figure 10. Faster and smoother transition – a subsidy to green firms



Note: The relative prices, capital, hours worked, and the neutral rate are normalised by the initial steady state and multiplied by 100.

5.4 Imperfect capital mobility

Imperfect capital mobility between the two sectors is a potentially important feature that may affect the neutral rate during the green transition. To quantify the effects of imperfect capital mobility, we introduce a capital adjustment cost in the green sector, $\mathcal{C}(I_t^G, K_{t-1}^G)$. This makes it costly to move capital from the fossil-based sector to the green sector. Formally, the adjustment cost is added to the law-of-motion of green capital stock in the following way,

$$K_t^G = I_t^G + (1-\delta)K_{t-1}^G - \mathcal{C}(I_t^G, K_{t-1}^G).$$

The adjustment cost function is assumed to be quadratic,

$$\mathcal{C}(I_t^G, K_{t-1}^G) = \frac{\kappa}{2}\left(\frac{I_t^G}{K_{t-1}^G} - 1\right)^2 K_{t-1}^G,$$

where the parameter κ determines the size of the adjustment cost. The capital stock in the fossil-based sector follows the standard law-of-motion,

$$K_t^F = I_t^F + (1-\delta)K_{t-1}^F.$$

The main purpose is to quantify the principal economic effects of imperfect capital mobility. We thus use the smooth transition paths for the carbon tax and the green subsidy from the previous sub-section. These paths avoid the erratic behaviour of the neutral rate that is implied by the suggested stepwise paths of the carbon tax and green subsidy, making the principal economic effects more clearly visible. This choice may come at the expense of some realism, but arguably the transition paths are very uncertain and the smooth transition paths are still in line with net-zero goal.

A carbon tax. Figure 11 shows the transition paths for green and fossil-based capital stocks as well as the neutral rates in the green and fossil-based sectors. For the capital stocks, the dashed line shows the transition under perfect capital mobility and the solid line shows the transition with a relatively high adjustment cost ($\kappa = 50$). As expected, the transition of the green capital stock to the new steady state becomes significantly slower, while the transition of the fossil-based capital stock remains largely unaffected.

Imperfect capital mobility implies that the neutral rates in the two sectors are not equalised. In the green sector, the neutral rate increases during the transition, and in the fossil-based sector it decreases. The green and fossil-based neutral rates are given by,

$$r_t^G = p_t^G \mathcal{F}'_{K_t^G},$$

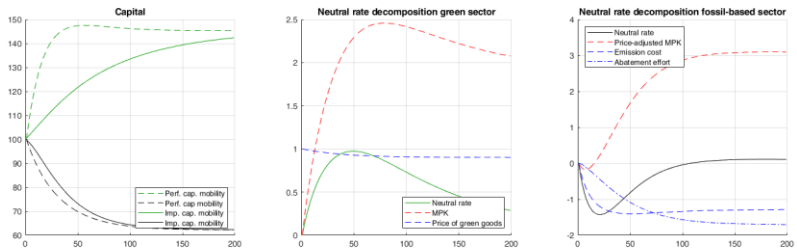
$$r_t^F = p_t^F \mathcal{F}'_{K_t^F} - \tau_t^E \mathcal{M}'_{K_{t,t}^F} \mathcal{F}'_{K_t^F} - \mathcal{A}'_{K_{t,t}^F} \mathcal{F}'_{K_t^F}.$$

Figure 11 shows that the increase in the green neutral rate is driven by a higher marginal product of green capital, whereas the decrease in the fossil-based neutral rate is due to the increased emissions costs and higher abatement efforts, i.e., the last two factors in the fossil-based neutral rate condition.

The capital adjustment cost parameter is not a so-called deep parameter that is invariant to changes in economic policies. The value of this parameter is therefore uncertain and difficult to calibrate. We therefore carry out sensitivity analysis with respect to different values of this parameter. Figure 12 shows how the neutral rates in the two sectors are affected when the adjustment cost parameter varies from 5 up to 50.

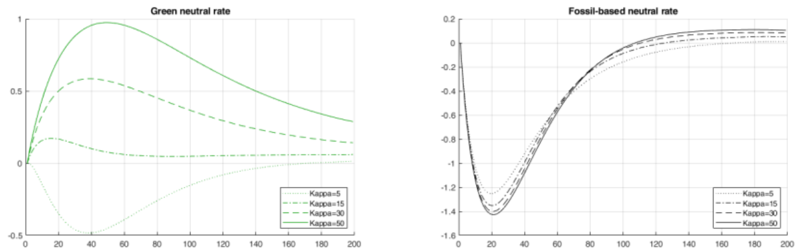
For low adjustments costs, the neutral rates fall in both sectors but notably more in the fossil-based sector. The fall in the green sector is 0.5 percentage points compared to 1.4 percentage points in the fossil-based sector. The neutral rate in the fossil-based sector is largely unaffected by the adjustment cost, while the green neutral rate increases as the adjustment cost becomes higher. For the very high adjustment cost ($\kappa = 50$), the increase is about 1 percentage point.

Figure 11. Perfect versus imperfect capital mobility – a carbon tax



Note: Capital is normalised by the initial steady state and multiplied by 100, while the other variables except for the relative price are deviations from steady state.

Figure 12. The neutral rate for different degrees capital mobility – a carbon tax



Note: Deviations from steady state (percentage points).

A subsidy to firms in the green sector. Figure 13 shows the effects on the capital stock and the neutral rates in the two sectors of imperfect capital mobility. The solid line shows the transition with a relatively high adjustment cost ($\kappa = 50$) and the dashed line under perfect capital mobility. As with the carbon tax, the green capital stock adjusts slower to the new steady state when capital is imperfectly mobile. In addition, the green neutral rate also increases, and the fossil-based neutral rate decreases. Quantitatively, however, the effects are significantly different compared to the carbon tax. The increase in the green neutral rate is very large, about 16 percentage points, while the decrease in the fossil-based neutral rate is only about 1 percentage point.

The green neutral rate is given by the following condition when examining the green subsidy,

$$r_t^G = p_t^G \mathcal{F}'_{K_t^G} + \varsigma_t^Y p_t^G \mathcal{F}'_{K_t^G},$$

i.e. the green neutral rate is given by the price-adjusted green marginal product of capital plus the product of the subsidy to the price-adjusted green marginal product. Figure 13 illustrates that most of the increase is due to the subsidy itself. The difference between the price-adjusted marginal product explains only a small part of the increase, while the product of the subsidy to the price-adjusted green marginal product almost fully explains the increase.

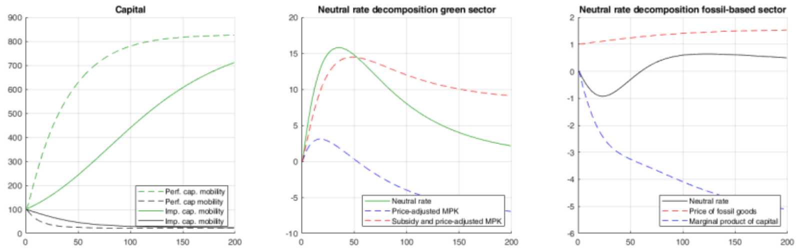
The fossil-based neutral rate is simply given by the product of the price of fossil-based goods and the marginal product of capital,

$$r_t^F = p_t^F \mathcal{F}'_{K_t^F},$$

Figure 13 shows that the fall in the fossil-based neutral interest rate is due the lower fossil-based marginal product of capital. Although, the higher price of fossil-based goods mitigates the fall. After some time, this factor leads to a somewhat higher fossil-based rate.

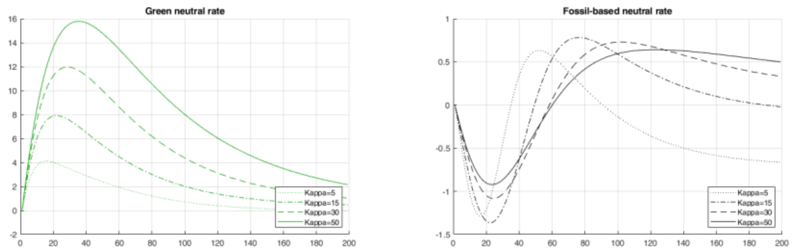
Figure 14 shows the sensitivity of the neutral rates in the two sectors when varying the adjustment cost parameter from 5 up to 50. The results are qualitatively similar to the carbon tax case; the higher the adjustment cost, the higher the green neutral rate becomes. Moreover, the fossil-based neutral rate is largely unaffected by the adjustment cost.

Figure 13. Perfect versus imperfect capital mobility – a subsidy to green firms



Note: Capital is normalised by the initial steady state and multiplied by 100, while the other variables except for the relative price are deviations from steady state.

Figure 14. The neutral rate for different degrees of capital mobility – a subsidy to green firms



Note: Deviations from steady state (percentage points).

6 Concluding remarks

We have examined how the green transition – implemented by either a carbon tax, green subsidies, or a policy of green preferences – may affect the neutral interest rate. We have considered a simple but standard economic framework to highlight the basic mechanisms and to provide some benchmark quantitative results. Future studies can extend this framework in different directions. NGFS (2024b) suggests that models studying economic implications of climate change should explore less standard frameworks that take into account heterogeneity and not fully rational behaviour. Another suggestion is to consider uncertainty by, for example, describing the evolution of climate policies as stochastic processes. Models could also move away from the Cobb-Douglas function to allow for a wider range of substitution elasticities among production inputs, and finally, to allow for input-output linkages.

The green transition affects firms' production plans and households' consumption patterns, but it also affects banks' and investors' behaviour and has international spill-over effects. Extending the model with financial markets and frictions to examine how the neutral rate can be affected by, for example, changes in asset prices and the risk of stranding assets can be of interest. Internationally, climate policies can affect competitiveness and prices of traded goods – and therefore the terms of trade and current account balances in different countries – with possible consequences for the neutral rate.

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