Navigating the Green Transition: The Role of Monetary Policy

Facundo Luna*

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Abstract

The transition to a low-carbon economy poses macroeconomic and financial stability challenges. Using a two-sector Environmental DSGE model with financial frictions and Epstein-Zin preferences, this paper explores how monetary policy can complement climate fiscal policies, like a carbon tax, to mitigate transition risks. We evaluate conventional and unconventional monetary policies, including emissions-inclusive Taylor Rules and Quantitative Easing (QE) programs.

Our findings shows that monetary policy can address transition risks without compromising its traditional mandate. The standard Taylor rule presents a balanced approach regarding Welfare and Loss Function approach. Green QE outperforms Neutral QE, yielding higher welfare and greater emissions reductions, especially when abatement is limited. Policies minimizing the Central Bank Loss Function achieve superior welfare outcomes compared to traditional and inflation-targeting rules, while keeping emissions in line. These results emphasize that monetary policy should prioritize stability, where emissions reductions emerging indirectly through financial markets, stressing the need for monetary-fiscal coordination in managing transition risks.

*Rutgers University - Economics Department, rl870@economics.rutgers.edu

1 Introduction

Climate change is an urgent global challenge that requires immediate action from policymakers, economists, and stakeholders. Within macroeconomics and finance, transition risks have gained prominence as economies shift toward a low-carbon future. These risks stem from the structural transformations necessary by climate policies, technological advances, and evolving consumer preferences (Feyen et al., 2020).

The transition to a low-carbon economy presents significant risks of economic and financial instability, particularly for carbon-intensive sectors that rely heavily on fossil fuels. Industries such as oil, gas, coal, steel, aluminum, cement, plastics, and greenhouse horticulture are especially vulnerable to asset devaluations, potentially leading to stranded assets and severe financial repercussions (Van der Ploeg and Rezai, 2020). These disruptions could trigger rising debt defaults, speculative bubbles in emerging industries, and abrupt asset revaluations, creating systemic risks that extend across the broader economy (Semieniuk et al., 2021).

In addition, financial feedback effects can further amplify macroeconomic impacts, with expectations playing a critical role. As capital is reallocated, carbon-intensive firms may experience declining profitability, asset devaluation, and tighter credit conditions, while low-carbon firms benefit from improved financing. This shift in investment flows can introduce market volatility and affect asset valuations in multiple sectors, stressing the financial complexities of the transition (NGFS, 2024).

According to the Intergovernmental Panel on Climate Change (IPCC, Lee et al. (2023)), there is a significant gap between the emissions reductions achieved under current policies and those required to meet the Paris Agreement targets, promoting the need for additional policy action by governments to meet their climate commitments (Lee et al., 2023). From a macroeconomic perspective, beyond the direct impacts of climate mitigation policies and other transition drivers, this policy gap introduces uncertainty about the transition pathway, which in turn can have macroeconomic consequences, such as affecting investment decisions and long-term economic planning.

To effectively manage these transition risks, it is essential to integrate them into macroeconomic models that account for financial frictions and environmental externalities. Doing so enables policymakers to assess the macroeconomic implications of climate policies and design strategies to mitigate financial instability during the transition to a low-carbon economy.

In this context, this paper employs a two-sector Environmental Dynamic Stochastic General Equi-

librium (E-DSGE) model with financial frictions, building on Gertler and Karadi (2011). The model incorporates environmental externalities through Epstein-Zin preferences, capturing pollution disutility, and features a brown sector that emits pollutants and a green sector that operates sustainably. Firms in both sectors issue bonds to finance capital, with banks and the Central Bank holding these bonds under leverage constraints, creating a spread between bond yields and deposit rates.

Within this framework, this study investigates the effectiveness of conventional and unconventional monetary policies in stabilizing the economy during this transition, focusing on their ability to reduce economic instability, emissions, and welfare costs. We examine whether neutral and green-biased Quantitative Easing (QE) programs differ significantly in managing financial crises triggered by a carbon tax, and assess how various Taylor Rule specifications influence macroeconomic and environmental outcomes. Specifically, we analyze how these policies balance economic stability with emissions reductions and their implications for societal welfare.

Our findings emphasize monetary policy's critical role in navigating the low-carbon transition's economic and financial challenges. Conventional monetary policy, when focused solely on inflation stabilization, can amplify output volatility following the introduction of a carbon tax. However, integrating emissions into the Taylor Rule enables the Central Bank to provide countercyclical support, easing the adjustment process while maintaining price stability.

We also find that Quantitative Easing (QE) policies can play a stabilizing role in the transition. While Neutral QE offers economic support but counteracts the effect of fiscal climate policy, Green QE generates stronger welfare gains and reduces emissions by reallocating financial resources toward cleaner investments. This effect is even more pronounced in the absence of abatement technology, discussing the potential of financial market interventions to accelerate decarbonization when firms lack other emissions reduction mechanisms.

From a policy perspective, the findings argues that monetary policy should remain centered on macroeconomic stability, with any impact on emissions occurring as a secondary effect rather than an active substitute for the fiscal climate policy. A Taylor Rule that minimizes the Central Bank Loss Function (CBLF) emerges as the most effective approach, delivering higher welfare gains than both a traditional and an inflation-targeting Taylor Rules, while ensuring that emissions remain within acceptable limits. This suggests that the optimal monetary policy framework should prioritize economic stability, allowing central bank interventions to enhance resilience while complementing fiscal climate policies without overstepping into their domain. Likewise, the CBLF-minimizing QE strategy is the

most consistent with the traditional central bank mandate, as it effectively stabilizes macroeconomic conditions while indirectly promoting emissions reductions through financial market adjustments.

These results contribute to the debate on Central Banks' roles in climate risk management (Battiston et al., 2017; Campiglio et al., 2018). While monetary policy cannot replace fiscal measures, it can mitigate financial instability and support capital reallocation. By integrating transition risks into macroeconomic models, our work stresses the need for monetary frameworks that complement climate policies, ensuring resilience during the low-carbon transition.

2 Literature Review

There is a growing body of macroeconomic research that employs Dynamic Stochastic General Equilibrium (DSGE) models with environmental externalities to examine the relationship between climate policies and business cycles. These models, commonly referred to as Environmental DSGE (E-DSGE) models,[1] provide a structured framework for assessing the macroeconomic implications of transitioning to a low-carbon economy. Among these models, our study aligns with those that incorporate financial frictions to analyze the effects of climate policies in the presence of credit market imperfections, with a particular focus on the role of monetary policy. This line of research is motivated by the concern that transition risks—arising from regulatory and policy changes, technological shifts, stranded asset risks, and evolving consumer preferences—could pose significant challenges to macroeconomic and financial stability.

A key debate in this literature centers on whether financial regulators and Central Banks should actively address climate change and to what extent they can do so. One approach involves the implementation of green-biased policies, such as green Quantitative Easing (QE), to facilitate the transition to a low-carbon economy (Annicchiarico et al., 2022). The role of unconventional monetary policy in mitigating transition risks has been explored in several studies implementing Green QE within an E-DSGE framework with financial frictions.

Ferrari and Nispi Landi (2024) find that a temporary Green QE program can effectively reduce emissions but has a limited impact on lowering the stock of atmospheric carbon if pollutants are slow-moving variables. In a related paper, (Ferrari and Nispi Landi, 2023) also show that the effectiveness of Green QE diminishes in the presence of a carbon tax, as the tax weakens the direct relationship between brown production and emissions. With a carbon tax in place, firms are incentivized to invest

[1] For an extensive review of E-DSGE models and business cycles, see Annicchiarico et al. (2022)

in abatement technologies, reducing emissions independently of Green QE interventions. Similarly, Abiry et al. (2022) show that while Green QE can partially crowd out private green investment, it only achieves a modest reduction in global temperatures, with a moderate carbon tax proving to be approximately four times more effective.

Other studies investigate the interactions between climate fiscal policy and Green QE. Benkhodja et al. (2023) argue that fiscal instruments such as carbon taxes, implicit taxes on brown loans, and subsidies for green goods support the green sector more effectively than Green QE. Their findings emphasize the importance of raising consumer awareness and improving the ability to consume green goods, as behavioral changes can significantly reinforce the effectiveness of public policies aimed at a low-carbon transition.

Papoutsi et al. (2021) examine the environmental impact of unconventional monetary policy, arguing that central bank asset purchases are inherently non-neutral due to the structure of bond markets, which favor carbon-intensive firms. Their findings shows the interplay between monetary and fiscal climate policies, emphasizing that carbon taxation should take the lead while monetary policy minimizes financial frictions. Unlike Papoutsi et al. (2021), we examine the welfare implications of QE and emissions-augmented Taylor Rules in the presence of carbon taxation and macroeconomic stability trade-offs.

Then, we find two studies that analyze both Macroprudential Policies and green QE in an E-DSGE framework with financial frictions. Benmir et al. (2024) explore the effectiveness of macroprudential regulation and Green QE in response to various shocks in an economy where the carbon tax is optimal. Their findings suggest that implementing sectoral, time-varying macroprudential weights on loans that favor the green sector fosters green capital accumulation and output growth with minimal welfare costs. In contrast, a Green QE policy substantially mitigates the impact of emissions-related risks on financial risk premia. Furthermore, their analysis indicates that while Green QE is more effective than macroprudential regulation in addressing premium inefficiencies, macroprudential tools are better suited to support the transition to clean technologies without significantly distorting welfare.

Diluiso et al. (2021) extend this analysis within a New Keynesian framework to assess how central banks can respond to climate change while maintaining macroeconomic and price stability. Their results indicate that Green QE can effectively stimulate economic activity following a financial shock in the fossil fuel sector. However, they find that its stabilizing effects are not markedly different from those of market-neutral asset purchase programs. Regarding macroprudential interventions, they

show that incentivizing the decarbonization of bank balance sheets through targeted capital requirements can significantly reduce the severity of financial crises. Nevertheless, this approach may also lead to a prolonged recovery phase, highlighting a key trade-off in the design of climate-aligned financial policies.

We contribute to this emerging but rapidly expanding DSGE literature on the role of central bank instruments in addressing environmental challenges and managing the macroeconomic consequences of the green transition. While existing research has concentrated mainly on the role of Green QE in enabling emissions reductions, our analysis emphasizes its broader role as a macroeconomic stabilization tool. By examining how Green QE and other monetary interventions interact with climate policies, we provide new insights into their capacity to cushion financial shocks and support economic stability and emission reductions during the transition to a low-carbon economy.

We contribute to the literature on whether central banks should adopt a dual mandate, balancing macroeconomic stability and employment objectives alongside inflation targeting, and to the broader discussion on optimal monetary policy (Erceg et al., 2000; Schmitt-Grohé and Uribe, 2007). While the traditional view asserts that central banks should focus solely on price stability to anchor expectations and minimize distortions (Clarida et al., 1999; Svensson, 2000; Vestin, 2000), Debortoli et al. (2019) argue that simple loss functions should place significant weight on economic activity, in some cases even greater than the weight on inflation. This debate has gained renewed relevance as central banks face challenges that extend beyond traditional macroeconomic concerns, including financial stability and, increasingly, transition risks related to climate change (Acharya, 2015; Agénor and Flamini, 2022; Chen et al., 2021; Krogstrup and Oman, 2019). While climate targets are generally considered the responsibility of fiscal policy, their macroeconomic implications raise essential questions about whether central banks should expand their mandates to include climate-related financial risks or remain strictly focused on inflation and output stabilization.

In terms of the interaction between conventional monetary policy and the green transition, McKibbin et al. (2020) analyze how monetary policy responds to climate change using the G-Cubed model[2]. Their findings indicate that inflation targeting exacerbates output declines under a carbon tax, while nominal income targeting mitigates these effects by stabilizing household balance sheets. Their results stress the importance of coordinating climate and monetary policy, as improper monetary responses to carbon pricing can heighten macroeconomic volatility. They argue that central banks should antic-

[2]The G-Cubed multi-country model is an intertemporal general equilibrium framework that the authors describe as a hybrid between DSGE and computable general equilibrium (CGE) models.

ipate and respond to both inflation increases and output contractions from climate policies.

Similarly, Chen et al. (2021) introduce a climate-augmented monetary policy rule within an E-DSGE model, analyzing how different monetary regimes, including a standard Taylor rule, respond to carbon taxes and cap-and-trade systems. They find that monetary policy must account for existing climate policies, as these influence inflation, price stability, and macroeconomic fluctuations. While they explore the role of emissions-gap targeting, which can enhance welfare but risks overburdening central banks, our analysis takes a different approach by evaluating Taylor rule specifications in response to carbon taxation, incorporating a countercyclical emissions target to mitigate the adverse macroeconomic effects of transition shocks.

More recently, Del Negro et al. (2023) construct a multi-sector New Keynesian model with calibrated input–output linkages to quantify how carbon taxation generates an inflation–output trade-off that is sizable yet short-lived, fading within approximately one year. In a Ramsey framework, Nakov and Thomas (2023) embeds climate externalities into a canonical New Keynesian model and demonstrates that, under efficient (socially optimal) carbon pricing, monetary policy can stabilize both inflation and output simultaneously. However, with realistic (suboptimal) tax levels, central banks revert to traditional price-stabilization objectives, with a modest role for green quantitative easing to accelerate the transition. Complementing these findings, Olovsson and Vestin (2023) employs a two-sector DSGE model to prove analytically that by targeting core or wage inflation and "seeing through" energy price changes, central banks can keep headline "greenflation" below 1% under a gradual carbon-tax schedule, thereby minimizing welfare costs. Our study differs by embedding financial intermediation frictions à la Gertler and Karadi and Epstein–Zin preferences with direct pollution disutility into an E-DSGE framework, allowing us to evaluate both conventional rate rules and unconventional asset-purchase programs under realistic transition-risk scenarios.

Building on this discussion, we examine how monetary policy adjustments, particularly through Quantitative Easing (QE) and emissions-augmented interest rate rules, influence macroeconomic volatility and assess whether a more flexible policy framework can enhance economic stability without compromising inflation control. Our objective is to determine the optimal mix of Unconventional and Conventional Monetary Policy during the transition to a low-carbon economy, adopting a dual approach that evaluates both welfare gains and the central bank's dual mandate of price stability and economic stability. This assessment is conducted using a Central Bank Loss Function (CBLF) and benchmarked against a baseline scenario where only climate policy is active in the case of QE. For

conventional policy, we compare an Inflation-Targeting Taylor Rule with alternative Taylor Rules incorporating different policy targets, allowing us to identify trade-offs and complementarities between monetary and fiscal climate interventions.

Additionally, we extend the conventional framework of production damages from pollution by incorporating Epstein-Zin consumer preferences, which explicitly account for disutility from environmental externalities. This refinement provides a more comprehensive perspective on how policy interventions directly impact welfare, as measured by household utility functions. By considering both the traditional production damages and the welfare costs of environmental degradation, our model captures broader and potentially more significant welfare implications than those considered in standard macroeconomic frameworks.

This approach, which accounts for environmental damage both in the production sector and directly in household utility, enables a more complete assessment of welfare trade-offs.

3 Model

Our model builds on elements from Diluiso et al. (2021) and Ferrari and Nispi Landi (2024). A key feature of these frameworks is a New Keynesian (NK) model with financial intermediation, a representative household, and a two-sector structure: a final goods sector aggregating heterogeneous intermediate production sectors (green and brown). The economy incorporates sector-specific capital inputs and multiple bank-held assets, with financial frictions arising from an agency problem that limits banks' ability to obtain funds from households, following Gertler and Karadi (2011). Nominal price rigidities make monetary policy central to real activity dynamics and the transmission of shocks. The sectoral structure enables the analysis of systemic spillover effects from climate policy and the associated transition risks.

A distinguishing feature of our model is the household's preferences. We introduce a recursive Epstein-Zin utility function with a negative externality from climate factors (Epstein and Zin (1991), Epstein and Zin (2013)). The inclusion of Epstein-Zin preferences introduces a crucial distinction between risk aversion and intertemporal elasticity of substitution (IES), allowing for a more flexible representation of household decision-making under climate transition risks. Unlike the standard CRRA utility function, which assumes a direct inverse relationship between risk aversion and IES, Epstein-Zin preferences enable agents to be highly risk-averse while still displaying a relatively high willingness to substitute consumption across time. This distinction is particularly relevant in the context

of climate policy, where households face long-term uncertainties about economic and environmental conditions.

The justification for using this utility function arises from the existing studies that apply this kind of preference to climate economics, demonstrating the importance of this approach (Ackerman et al. (2013), Hambel et al. (2021)). They show that it leads to optimal solutions and policy recommendations that significantly differ from the conventional approach based on the Ramsey equation and the expected utility framework (Ackerman et al. (2013)).

In our model, Epstein-Zin's preferences amplify the welfare effects of carbon taxation and monetary policy interventions due to how agents discount these future costs. The recursive structure of Epstein-Zin utility introduces forward-looking behavior where households not only consider immediate consumption and labor-leisure trade-offs but also form expectations about long-term welfare losses due to environmental degradation. In Appendix A, we show the key differences in CRRA preferences.

To analyze the transition, using a deterministic algorithm, we examine the transition path to a new low-carbon steady state following the implementation of an aggressive carbon tax. This exercise triggers several responses in the economy. First, we can expect an increase in the price of brown goods, generating inflationary pressures. At the same time, the carbon tax leads to a decline in economic output, partially offsetting the inflationary effect on overall price levels. Furthermore, this scenario results in a sharp devaluation of fossil-based assets. Such a sudden drop in their value could have severe consequences, particularly for bank capital stability. The deterioration of bank balance sheets may disrupt credit flows, leading to contagion and cascading effects throughout the broader economy. This instability poses a significant risk to financial markets and macroeconomic stability, raising critical concerns for central banks regarding monetary policy transmission, systemic risk, and financial sector resilience in the face of climate transition shocks.

The following subsections present more details about the different sectors in this model in this context.

3.1 Households

We follow Barrage (2020) and propose a continuum of infinitely lived households with preferences over consumption, leisure, and climate. Therefore, carbon emissions not only affect production (as the standard way to introduce environmental externality) but also negatively affect household utility.

In each household, there are bankers and workers. Each banker manages a financial intermediary and transfers profits to the household. Nevertheless, households cannot lend their money to a financial intermediary owned by one of their members. Household members who are workers supply labor inelastically and return their salaries to their households. They can switch between the two occupations over time, but are exogenously determined in such a way that keeps the relative proportions constant.

The representative Household has a utility function over streams of consumption (c_t) and leisure ($1 - L_t$):

$$V_t = \left((1-\beta) \left(\left(c_t^{\omega} \ (1-L_t)^{1-\omega} \right)^{1-\rho} - (\alpha_0 \, X_t)^{1-\rho} \right) + \beta \left[\mathbb{E}_t (V_{t+1}^{1-\sigma}) \right]^{\frac{1-\rho}{1-\sigma}} \right)^{\frac{1}{1-\rho}} \tag{1}$$

Where ω is the utility weight attached to consumption, β is the discount factor, $\sigma > 0$ is the risk aversion parameter, $\psi > 0$ is the elasticity of inter-temporal substitution (EIS) parameter with $\rho = \frac{1}{\psi}$ and $L_t = \left(L_{b,t}^{1+\rho_l} + L_{g,t}^{1+\rho_l} \right)^{\frac{1}{1+\rho_l}}$ is the labor composite, being ρl the elasticity of substitution. Additionally, α_0 is a parameter that represents the disutility to the stock of pollution X_t.

Following Barrage (2020), the preference formulation over climate factors (in this case, emissions) ensures that the emissions risk aversion coefficient is identical for utility damages and equivalent consumption losses. This approach provides a consistent framework for quantifying climate-related welfare impacts.

The budget constraint for the Household is:

$$c_t + D_{t+1} = w_{b,t} L_{b,t} + w_{g,t} L_{g,t} + T_t + R_t D_t + \Pi_{t,g} + \Pi_{t,b} + \Phi_t \tag{2}$$

With c_t is the consumption in period t, $L_{t,k}$ are the amount of hours supplied to each sector (green and brown), $w_{k,t}$ is the real wage paid to the Households. Φ_t are profits from the ownership of non-financial firms that will serve as start-up funds for the new bankers, $\Pi_{t,k}$ are the profit for non-financial firms, and T_t are lump sum taxes. Also, we assume that intermediary deposits and government bonds are one-period bonds so that $R_t D_t$ are the interest received on deposits, and D_{t+1} are the decision on the amount of deposit in each period.

We assume, as in Gertler and Karadi (2011), that a fraction $1 - f$ of household members are workers, while the remaining fraction f are bankers. Over time, individuals can transition between these two occupations. Specifically, a banker in the current period remains a banker in the next period with probability χ, independent of their past occupation history, including the duration for which they

have been a banker.

The recursive representation of the Household problem is:

$$V_t = \max_{c_t, L_t, D_{t+1}} \left((1-\beta) \left(\left({c_t}^{\omega} \ (1-L_t)^{1-\omega} \right)^{1-\rho} - \alpha_0 X_t^{1-\rho} \right) + \beta \left[(\mathbb{E}_t(V_{t+1}^{1-\sigma}))^{\frac{1}{1-\sigma}} \right]^{1-\rho} \right)^{\frac{1}{1-\rho}}$$

$$\text{s.t.} \quad c_t + D_{t+1} = w_{b,t} L_{b,t} + w_{g,t} L_{g,t} - T_t + R_t D_t + \Pi_{g,t} + \Pi_{b,t} + \Phi_t$$

$$L_t = \left(L_{b,t}^{1+\rho_l} + L_{g,t}^{1+\rho_l} \right)^{\frac{1}{1+\rho_l}}$$

The First order conditions of this problem give us the following equations:

Labor supply conditions:

$$(1-L_t) \left(L_{b,t}^{1+\rho_l} + L_{g,t}^{1+\rho_l} \right)^{\frac{\rho_l}{1+\rho_l}} L_{b,t}^{\rho_l} = \frac{c_t}{w_{b,t}} \frac{1-\omega}{\omega}$$

$$(1-L_t) \left(L_{b,t}^{1+\rho_l} + L_{g,t}^{1+\rho_l} \right)^{\frac{\rho_l}{1+\rho_l}} L_{g,t}^{\rho_l} = \frac{c_t}{w_{g,t}} \frac{1-\omega}{\omega}$$

The Stochastic Discount Factor is:

$$M_{t,t+1} = \beta \frac{C_t}{C_{t+1}} \frac{\left(C_{t+1}^{\omega} (1-L_{t+1})^{1-\omega} \right)^{1-\rho}}{\left(C_t^{\omega} (1-L_t)^{1-\omega} \right)^{1-\rho}} \left(\frac{V_{t+1}^{1-\sigma}}{\mathbb{E}_t \left(V_{t+1} \right)^{1-\sigma}} \right)^{\frac{\rho-\sigma}{1-\sigma}}$$

And the Euler Equation:

$$\mathbb{E}_t \, M_{t,t+1} R_{t+1} = 1$$

3.2 Final Goods Producers

The representative final-good firm uses a standard CES aggregator to produce the final good Y_t:

$$Y_t = \left[\int_0^1 y_t(i)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \tag{3}$$

where the intermediate good produced by the intermediate firm i is $y_t(i)$ sold at price $p_t(i)$. The final goods firm solves:

$$\max \ P_t Y_t - \int_0^1 p_t(i) y_t(i) di$$

$$\text{s.t} \quad Y_t = \left[\int_0^1 y_t(i)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}$$

With P_t being the price level. The solution to this problem is the demand function for each firm i:

$$y_t(i) = y_t \left(\frac{p_t(i)}{p_t} \right)^{-\epsilon} \tag{4}$$

3.3 Intermediate Producers

We have a continuum of intermediate firms i, producing a differentiated input using a CES bundle of green $y_{g,t}$ and brown $y_{b,t}$ goods:

$$y_t(i) = \left[(1-\zeta)^{\frac{1}{\gamma}} (y_{g,t}(i))^{\frac{\gamma-1}{\gamma}} + \zeta^{\frac{1}{\gamma}} (y_{b,t}(i))^{\frac{\gamma-1}{\gamma}} \right] \tag{5}$$

Where ζ is the share of brown goods in total output and γ is the elasticity of substitution between brown and green goods:

The intermediate firm i faces two optimization problems: an intertemporal problem for determining the optimal input combination and an intertemporal problem for setting the price. The primary objective is to minimize costs while ensuring a given level of production:

$$\min \; p_{g,t} y_{g,t}(i) + p_{b,t} y_{b,t}(i)$$

$$\text{st} \; y_t(i) = \left[(1-\zeta)^{\frac{1}{\gamma}} (y_{g,t}(i))^{\frac{\gamma-1}{\gamma}} + \zeta^{\frac{1}{\gamma}} (y_{b,t}(i))^{\frac{\gamma-1}{\gamma}} \right]$$

Where $p_{g,t}$ represents the price of green production and $p_{b,t}$ denotes the price of brown production, both expressed relative to the price level P_t, the optimization problem results in the following demand functions for the green and brown inputs:

$$y_{g,t} = (1-\zeta) \left(\frac{p_{g,t}}{MC_t} \right)^{-\gamma} y_t(i) \tag{6}$$

$$y_{b,t} = \zeta \left(\frac{p_{b,t}}{MC_t} \right)^{-\gamma} y_t(i) \tag{7}$$

In this monopolistic competition setting, firms have the autonomy to set prices based on the demand they face from the final-good firm (4). When adjusting their price inflation concerning the Central Bank target inflation, firm i incurs quadratic adjustment costs à la Rotemberg (1982). Therefore,

the intertemporal problem for firm i is:

$$\max_{\{p_t(i)\}_{i=0}^{\infty}} \quad E_0\left[M_{t,0}\left(\left(\frac{p_t(i)}{P_t}\right)^{-\epsilon}\left(\frac{p_t(i)}{P_t}-MC_t\right)-\frac{\kappa_p}{2}\left(\frac{p_t(i)}{p_{t-1}(i)}-\bar{\pi}\right)^2 y_t\right)\right]$$

From a symmetric equilibrium, we get the standard Philips Curve:

$$\pi_t(\pi_t-\bar{\pi})=\mathbb{E}_t\left[M_{t,t+1}\pi_{t+1}(\pi_{t+1}-\bar{\pi})\frac{y_{t+1}}{y_t}\right]+\frac{\epsilon}{\kappa_p}\left(MC_t-\frac{\epsilon-1}{\epsilon}\right) \tag{8}$$

Where the marginal cost is $MC_t=\left[(1-\zeta)p_{g,t}^{1-\gamma}+\zeta p_{b,t}^{1-\gamma}\right]^{\frac{1}{1-\gamma}}$

3.4 Green and Brown producers

In this part of the economy, we include the environmental externality as an aggregate cost equivalently to an environmental damage cost. Following the work of Heutel (2012), firms have a Cobb-Douglas production where the negative externalities negatively affect the environment, and the stock of pollutants alters the production possibilities of firms in the sense of Nordhaus (2017):

$$y_{k,t}=A_t(\xi_{k,t}K_{t-1,k})^{\alpha}L_{t,k}^{1-\alpha} \tag{9}$$

With A_t being the productivity of the firms in the sector k, and $A_t=(1-(D_0+D_1X_t+D_2X_t^2)a)$ is affected by the pollution stock through a damage function, standard in the DICE models like in Nordhaus (2008) and a is TFP shock that follows an AR(1) process.

To model the evolution of the stock of carbon emissions, we follow Heutel (2012). For simplicity, we assume that only the brown sector pollute. The equation for the law of motion of the stock of pollution is:

$$X_t=(1-\delta_x)X_{t-1}+e_t+e^* \tag{10}$$

Being e_t the emission from the brown firms, δ_x is the decay rate of the stock of pollution, and e^* is a constant level of emissions of the rest of the world. The amount of emissions evolves accordingly to the level of output where $1-\lambda$ is the elasticity of emissions and the fraction of emissions that the brown firms do not abate:

$$e_t=(1-ab_t)y_{b,t}^{1-\lambda} \tag{11}$$

In the case of Brown firms, they maximize profits by choosing labor, capital, and the level of emis-

sion abatement to produce output used by intermediate firms. Also, issues bonds $b_{b,t}$ to finance capital purchase $b_{b,t} = q_{b,t}K_{b,t}$. Additionally, they are subjected to a carbon tax on their level of emissions, and to abate on unit of emissions, they must pay a cost $Z_t = \left[\theta_1 ab_t^{\theta_2} + \frac{1}{2}\kappa_e(ab_t - ab_{t-1})^2\right] y_{b,t}$. In this abatement cost function, θ_1 and θ_2 are the cost efficiency of abatement parameters and are subject to adjustment costs κ_e [3]

Hence, the maximization problem for the brown firms is:

$$\max \quad p_{b,t}y_{b,t} - w_{b,t}L_{b,t} - r_{kb,t}K_{b,t-1} - \tau_t e_t - Z_t$$

With $r_{k,b,t} = r_{b,t}q_{b,t-1} - (1-\delta)q_{b,t}$ being the rental rate of capital for each type of firm and $\xi_{b,t}$ is a capital quality shock that follows an AR(1) process. The first-order conditions for this problem are:

$$(1-\alpha)y_{b,t}\left(p_{b,t} - \tau_t(1-ab_t)(1-\lambda)y_{b,t}^{-\lambda} - \kappa_e(ab_t - ab_{t-1})\right) = L_{b,t}w_{b,t}$$

$$\alpha y_{b,t}\left(p_{b,t} - \tau_t(1-ab_t)(1-\lambda)y_{b,t}^{-\lambda} - \kappa_e(ab_t - ab_{t-1})\right) = k_{b,t-1}r_{k,b,t}$$

$$ab_t = \frac{\left(\tau_t * y_{b,t}^{-\lambda} + \kappa_e ab_{t-1} + \kappa_e y_{b,t-1}/y_{b,t} ab_{t+1}\right)}{\theta_2\theta_1 ab_t^{(\theta_2-2)} + \kappa_e(1 + y_{b,t+1}/y_{b,t})}$$

Analogously, green firms are not subject to the carbon tax or abatement costs, so the first-order conditions for these firms are:

$$(1-\alpha)y_{g,t}p_{g,t} = L_{g,t}w_{g,t}$$

$$\alpha y_{g,t}p_{g,t} = k_{g,t-1}r_{k,g,t}$$

3.5 Capital Producers

Capital producers acquire the output generated by final-good firms and non-depreciated capital from intermediate firms to facilitate physical capital production and face investment adjustment costs. Subsequently, green and brown firms purchase the capital. Capital producers solve:

$$\max \ \mathbb{E}_0 \sum_{i=0}^{\infty} M_{0,t} \sum_{k=b,g} \left[q_{k,t}k_{k,t} - (1-\delta)q_{k,t}k_{k,t-1} - i_{k,t}\right]$$

[3] This adjustment introduces a more realistic dynamic for the emissions path. Without it, models like Carattini et al. (2023), which do not include abatement adjustment costs, result in emissions reaching the new steady-state level immediately after implementing a carbon tax.

$$\text{s.t. } k_{k,t} = (1-\delta)k_{k,t-1} + \left[1 - \frac{\kappa_I}{2}\left(\frac{i_{k,t}}{i_{k,t-1}} - 1\right)^2\right] i_{k,t}$$

Where $i_{k,t}$ is the investment in each sector $k = g, b$. The first-order conditions for each type of capital are:

$$1 = q_{k,t}\left(1 - \frac{\kappa_I}{2}\left(\frac{i_{k,t}}{i_{k,t-1}} - 1\right)^2 - \frac{i_{k,t}\,\kappa_I\left(\frac{i_{k,t}}{i_{k,t-1}} - 1\right)}{i_{k,t-1}}\right) + \mathbb{E}_t\, M_{t,t+1}\,\kappa_I\, q_{k,t+1}\left(\frac{i_{k,t+1}}{i_{b,t}} - 1\right)\left(\frac{i_{k,t+1}}{i_{k,t}}\right)^2$$

3.6 Financial Intermediaries

Financial intermediaries enable the introduction of financial frictions into the model through a borrowing constraint faced by banks. By incorporating credit market frictions in the banking sector, we capture a key source of macroeconomic fluctuations, making the model well-suited for analyzing transition risk. We follow Ferrari and Nispi Landi (2024) and Carattini et al. (2023) in modeling this sector. Additionally, Carattini et al. (2023) shows that an economy with financial frictions experiences a deeper recession than a frictionless economy, amplifying the transition risks.

Including financial frictions is crucial for understanding transition risk because credit constraints and risk premia adjustments can significantly amplify the economic impact of climate policies. When carbon-intensive sectors face policy shocks, such as the implementation of a carbon tax or stricter environmental regulations, the value of brown assets declines, reducing the collateral available for borrowing. This deterioration in balance sheets can lead to tighter credit conditions, higher financing costs, and even a contraction in economic activity.

In each period, banks raise deposits from households and lend to green and brown producers[4]. The balance sheet of the typical bank in time t is equal to:

$$b^f_{g,t} + b^f_{b,t} = NW_t + D_t \tag{12}$$

Where $b^f_{k,t}$ are bonds held by banks on green and brown firms with their respective prices $q_{t,k}$. On the right-hand side, we have the net worth NW_t and D_t deposits from the Households. To break the equality between green and brown rates, we assume that banks pay a quadratic cost when they change the fraction of green bonds out of total bonds concerning the steady-state level b^*.

This assumption captures the idea that shifting portfolios between green and brown assets is not

[4]In Appendix C we show the full derivation of the Financial Intermediares problem

frictionless, reflecting real-world constraints such as capital reallocation frictions, regulatory compliance costs, or internal risk management policies.

By introducing this cost, we create a wedge between the returns on green and brown bonds, preventing them from adjusting instantaneously to changes in market conditions. This mechanism allows the model to capture key financial dynamics associated with the low-carbon transition. For example, if green investments become more attractive due to policy incentives or market shifts, banks may face costs when reallocating their portfolios, slowing the response to new conditions. Similarly, in periods of financial distress, banks may be reluctant to increase green bond holdings even if returns rise due to the associated adjustment costs.

The net worth evolves as follows:

$$NW_t = r_{g,t} b^f_{g,t-1} + r_{b,t} b^f_{b,t-1} - \frac{r_{t-1}}{\pi_t} D_{t-1} - \frac{\kappa_F}{2} NW_{t-1} \left[\frac{b^f_{g,t-1}}{b^f_{t-1}} - b^* \right]^2 \tag{13}$$

Combining (12) and (13), we get an alternative equation for the net worth regarding the prior net worth value. The law of motion of net worth becomes:

$$\frac{NW_t}{NW_{t-1}} = \left(r_{g,t} - \frac{r_t}{\pi_{t+1}} \right) b^f_{g,t-1} + \left(r_{b,t} - \frac{r_t}{\pi_{t+1}} \right) b^f_{b,t-1} - \frac{r_t}{\pi_{t+1}} - \frac{\kappa_F}{2} \left[\frac{b^f_{g,t-1}}{b^f_{t-1}} - b^* \right]^2 \tag{14}$$

Where $r_{k,t} - \frac{r_t}{\pi_{t+1}}$ represents the risk premium specific to each sector. To prevent banks from excessively expanding assets in a sector, an agency problem is assumed where bankers can choose to divert a portion of available funds at the start of each period. If the intermediary defaults on its debt, depositors can force it into bankruptcy and recover a portion of its assets. Deposit amounts are limited by the value of the bank and the portion of funds that can be diverted, as depositors recognize the bank's incentive to divert funds. Following Gertler and Karadi (2011), we assume that this regulator requires that the discounted value of the bankers' net worth should be greater than or equal to the current value of assets:

$$V^f_t \geq \theta_t \left(b^f_{g,t} + b^f_{b,t} \right) \tag{15}$$

In this equation θ_t is the share of assets the banker can divert.

With probability $1 - \chi$, a banker exits the market getting NW_{t+1} at the beginning of period $t + 1$, where these resources are transferred to households. With probability χ, a banker continues in this

activity. Therefore, the value of a bank is:

$$V_t^f = \max \ \mathbb{E}_t \left[\sum_{i=0}^{\infty} (1-\chi)\chi^i M_{t,t+i} NW_{t+1+i} \right] \tag{16}$$

As is usual in this kind of models, we assume that the condition (15) is binding. Therefore, the problem if each financial intermediary is to maximize (16) subject to (14) and (15). The first order conditions for the bank are:

$$lev_t = \frac{M_{t,t+1}\nu_{t+1} \left(\frac{r_t}{\pi_{t+1}} + \left(r_{g,t+1} - r_{b,t+1} \right) lev_{g,t} - \frac{\kappa_F}{2} \left(\frac{lev_{g,t}}{lev_t} - b^* \right)^2 \right)}{\theta - M_{t,t+1}\nu_{t+1} \left(r_{b,t+1} - \frac{r_t}{\pi_{t+1}} \right)}$$

$$\mathbb{E}_t \, M_{t,t+1}\nu_{t+1} \left(r_{g,t+1} - r_{b,t+1} - \left(\frac{lev_{g,t}}{lev_t} - b^* \right) \frac{\kappa_F}{lev_t} \right) = 0$$

Where $lev_t = \frac{b_t^f}{NW_t}$ is the leverage and $lev_t^g = \frac{b_{g,t}^f}{NW_t}$ is the green leverage and ν_t can be considered as the bank's discount factor:

$$\nu_t = 1 - \chi + \nu_{t+1} \, \mathbb{E}_t \, M_{t,t+1} \chi \left(\frac{r_t}{\pi_{t+1}} + \left(r_{g,t+1} - r_{b,t+1} \right) lev_{g,t} + lev_t \left(r_{b,t+1} - \frac{r_t}{\pi_{t+1}} \right) - \frac{\kappa_F}{2} \left(\frac{lev_{g,t}}{lev_t} - b^* \right)^2 \right)$$

Then, the net worth comprises the net worth of new bankers and existing banks $NW_t = NW_{n,t} + NW_{e,t}$. Also, recall that a fraction χ of the banker remains in the financial intermediation activity in $t-1$, then we have

$$NW_{e,t} = \chi \left[(r_{g,t} - r_{b,t}) lev_{t-1}^g + (r_{b,t} - \frac{r_{t-1}}{\pi_t}) lev_{t-1} + \frac{r_{t-1}}{\pi_t} - \frac{\kappa_F}{2} \left(\frac{lev_{t-1}^g}{lev_{t-1}} - b^* \right)^2 \right] \tag{17}$$

And the new bankers receive a fraction $\frac{\iota}{1-\chi}$ of the net worth of exiting bankers as a start-up funding, getting $NW_{n,t} = \iota b_t^f$. Combining these two equations, we get the aggregate net worth evolution:

$$NW_t = \chi \left(\frac{r_{t-1}}{\pi_t} + \left(r_{b,t} - \frac{r_{t-1}}{\pi_t} \right) lev_{t-1} + \left(r_{g,t} - r_{b,t} \right) lev_{t-1}^g - \frac{\kappa_F}{2} \left(\frac{lev_{g,t-1}}{lev_{t-1}} - b^* \right)^2 \right) NW_{t-1} + \iota b_t^f$$

3.7 Central Banks and Government

In our baseline scenario, monetary policy follows a standard Taylor rule with interest rate smoothing:

$$\frac{r_t}{\bar{r}} = \left(\frac{r_{t-1}}{\bar{r}}\right)^{\rho_r} \left[\left(\frac{\pi_t}{\overline{\pi}}\right)^{\rho_\pi} \left(\frac{Y_t}{\overline{Y^*}}\right)^{\rho_y}\right]^{1-\rho_r} e_t^{m_t}, \tag{18}$$

where r_t is the risk-free nominal interest rate, $\bar{r}$ is its steady-state value, π_t represents inflation, and $\overline{\pi}$ is the target inflation rate. The term $e_t^{m_t}$ accounts for monetary policy shocks, while ρ_r governs interest rate smoothing. The parameters ρ_π and ρ_y determine the responsiveness of monetary policy to inflation and output deviations, respectively.

Monetary policy is crucial in mitigating the economic disruptions induced by a carbon tax. Introducing carbon pricing increases production costs, creating inflationary pressures while reducing output. A Taylor rule with interest rate smoothing allows the central bank to balance these opposing forces, preventing excessive monetary tightening or loosening that could destabilize the economy. By avoiding an overreaction to short-term fluctuations, the central bank facilitates a smoother transition to a low-carbon economy while maintaining price stability.

We consider variations of the Taylor rule to explore different policy responses to transition risk. The first alternative prioritizes inflation stabilization, reflecting the argument that central banks should focus exclusively on price stability rather than broader economic objectives:

$$\frac{r_t}{\bar{r}} = \left(\frac{r_{t-1}}{\bar{r}}\right)^{\rho_r} \left[\left(\frac{\pi_t}{\overline{\pi}}\right)^{\rho_\pi}\right]^{1-\rho_r} e_t^{m_t}. \tag{19}$$

Since this rule disregards output stabilization, the central bank may respond more aggressively to carbon tax-induced inflation, potentially tightening the policy even if the economy transitions. While this approach may prevent inflation expectations from de-anchoring, it risks exacerbating output losses and delaying green investments.

Alternatively, we extend the Taylor rule to incorporate an explicit emissions target, as in Chen et al. (2021):

$$\frac{r_t}{\bar{r}} = \left(\frac{r_{t-1}}{\bar{r}}\right)^{\rho_r} \left[\left(\frac{\pi_t}{\overline{\pi}}\right)^{\rho_\pi} \left(\frac{Y_t}{\overline{Y^*}}\right)^{\rho_y} \left(\frac{e_{t-1}}{e_{t-2}}\right)^{\rho_e}\right]^{1-\rho_r} e_t^{m_t}. \tag{20}$$

Here, $\frac{e_{t-1}}{e_{t-2}}$ represents the growth rate of the emissions, and ρ_e captures the sensitivity of the policy to the fluctuation of emissions. This rule enables the central bank to integrate environmental considerations into its decision-making, potentially offset by the contractionary effects of carbon pricing. Since emissions are a byproduct of brown-sector output and respond to production shifts and abatement mechanisms, this policy provides countercyclical support while ensuring a smoother transition.

Emissions are incorporated with a one-period lag to reflect real-world data availability constraints.

In addition to interest rate policies, we explore the role of unconventional monetary policy through neutral and green-biased Quantitative Easing (QE). The central bank can purchase both green and brown assets by issuing short-term bonds (we assume that are perfect substitutes to Deposits D_t), leading to the balance sheet condition:

$$b_t^G = b_{g,t}^G + b_{b,t}^G. \tag{21}$$

where $b_{k,t}^G = \mu_t b_{k,t}$. The central bank determines the scale of asset purchases. Under the deterministic transition scenario, QE policies can be implemented as temporary or permanent asset purchase programs. Neutral QE maintains market neutrality, providing liquidity without influencing risk premia, while Green QE actively reshapes credit allocation. The effectiveness of these policies depends on their ability to mitigate financial instability while supporting the transition to a low-carbon economy.

Green QE, by contrast, introduces a bias in favor of green assets ($\mu_{g,t}$) allows the central bank to shift its portfolio composition, favoring green bonds while reducing exposure to brown assets. In doing so, Green QE reduces the financing costs of green investment while increasing the risk premia for high-carbon sectors, incentivizing capital reallocation toward low-carbon production.

When these credit policies are implemented, the profits generated through public financial intermediation are transferred to the households in a lump sum manner[5].

Additionally, as in Gertler and Karadi (2011), we assume that the central bank is less efficient than private intermediaries when lending to the private sector but has the advantage of elastically obtaining funds by issuing risk-free government debt (perfect substitute to deposit). The cost of the Central Bank intermediation is fixed to the parameter ς, being the total cost $\varsigma b_t^G = \varsigma \mu b_t$. We are conservative and assume that the values of this cost is of 10 basis points, which according to Gertler and Karadi (2011) is probably quite large for assets like agency backed mortgage securities and commercial paper. This is because they assume that for reasonable values of efficiency costs (at most 10 basis points), the net gains from responding to crisis periods with Quantitative Easing may be significant.

Unlike private financial institutions, it is not subject to balance sheet constraints. Then, during the transition, when private intermediaries face tighter balance sheet constraints, the relative benefits of central bank intermediation increase, enhancing its role in stabilizing financial markets and the overall

[5]It issues government bonds $D_{g,t}$ to fund this activity. Its net earnings from intermediation are $\left(r_{g,t} - \frac{r_t}{\pi_{t+1}}\right) b_{g,t-1}^G + \left(r_{b,t} - \frac{r_t}{\pi_{t+1}}\right) b_{b,t-1}^G$.

economy.

From a policy perspective, Green QE offers a mechanism for central banks to influence the financial transition without explicitly targeting emissions. Unlike approaches incorporating emissions into interest rate policy, Green QE operates through capital markets, directing credit toward sustainable investments while maintaining financial stability. This approach aligns with the broader discussion on whether central banks should adopt an explicit climate mandate or use existing tools to mitigate transition risks (see Ferrari and Nispi Landi (2024)).

To assess the performance of different monetary policy strategies, we evaluate welfare changes and variations in the central bank's loss function following Debortoli et al. (2019):

$$Loss_t^{\text{CB}} = \lambda_\pi(\pi_t)^2 + \lambda_{\Delta_r}(\Delta r_t)^2 + \lambda_y(y_t - y^*)^2. \tag{22}$$

where λ_k are weight parameters, $\Delta r_t = r_t - r_{t-1}$ captures interest rate volatility, and $y_t - y^*$ is output-gap. This function represents the trade-off between stabilizing inflation and minimizing fluctuations in output. It captures the dual mandate of many central banks, such as the European Central Bank, which seek to ensure both price and economic stability.

We adopt the optimal weights calibration computed by Debortoli et al. (2019) as a benchmark:

$$\lambda_\pi = 1, \quad \lambda_{\Delta r} = 0.077, \quad \lambda_y = 1.042$$

These values reflect the central bank's primary focus on inflation and output stability. In addition, the inclusion of the volatility of interest rates is motivated by the reference to 'aversion to interest rate variability' and concerns about financial stability. The relative weight on interest rate volatility ensures gradual adjustments in monetary policy, whereas the weight on output stabilization acknowledges the trade-offs in responding to economic fluctuations (Debortoli et al., 2019).

Finally, to close the model, we define the following final goods market-clearing condition:

$$y_t = c_t + I_t + \frac{\kappa_F}{2} NW_{t-1} \left[\frac{b^f_{g,t-1}}{b^f_{t-1}} - b^* \right]^2 + \frac{\kappa_p}{2} \left(\frac{p_t(i)}{p_{t-1}(i)} - \bar{\pi} \right)^2 y_t + \varsigma \mu b_t + Z_t \tag{23}$$

3.8 Data and Calibration

The model is calibrated at a quarterly frequency specifically for the euro area. It's important to note that the euro area comprises countries with diverse emissions profiles and economic structures. How-

ever, for simplicity's sake and alignment with existing literature, we treat the euro area as a unified entity.

We rely on the New Area-Wide Model (NAWM-II) second version to establish our calibration, as Coenen et al. (2018) developed. The NAWM-II is an estimated Dynamic Stochastic General Equilibrium (DSGE) model specifically designed for the euro area. We utilize this model to calibrate various economic and banking parameters and parameters used in Ferrari and Nispi Landi (2024), Barrage (2020), Carattini et al. (2023), and Gertler and Karadi (2011). Table I presents the values for the calibration of the Baseline model. See Appendix B for full details about the calibration of targeted parameters used in this first exercise.

Table 1: Macroeconomic and Household Parameters

Parameter	Description	Value	Source
β	Discount factor	0.995	Standard
α	Capital share in production	0.36	Coenen et al. (2018)
ψ	Intertemporal elasticity of substitution	0.5	Standard
σ	Risk aversion coefficient	2	Carattini et al. (2023)
ω	Weight of consumption in utility	0.32	Barrage (2020)
δ	Capital depreciation rate	2.5%	Standard
ρ_l	Elasticity of substitution for labor hours	1	Carattini et al. (2023)
γ	Elasticity of substitution for brown and green goods	2	Carattini et al. (2023)
ζ	Weight of brown goods in consumption	0.8	Giovanardi et al. (2023)
κ_p	Price adjustment cost	70	Match Calvo = 0.82
$\bar{\pi}$	Target inflation rate	1.005	Coenen et al. (2018)
κ_I	Investment adjustment cost	10.78	Coenen et al. (2018)
$\bar{r}$	Steady-state nominal interest rate	1.01	Coenen et al. (2018)
ρ_r	Interest rate smoothing parameter in Taylor rule	0.93	Coenen et al. (2018)
ρ_π	Inflation responsiveness in Taylor rule	2.74	Coenen et al. (2018)
ρ_y	Output gap responsiveness in Taylor rule	0.03	Coenen et al. (2018)
ρ_a	Persistence of technology shock	0.93	Coenen et al. (2018)
ρ_ξ	Persistence of capital quality shock	0.66	Gertler and Karadi (2011)
ϑ	Intensity of the QE rule	10	Gertler and Karadi (2011)

Most standard parameters come from NAWM-II, such as the share of capital in production, the elasticity of differentiated goods, target inflation, investment adjustment costs, bank survival proba-

bility, and the parameter of the Taylor rule and the productivity process. Then, we follow Ferrari and Nispi Landi (2024) and set β to achieve a steady-state annualized real interest rate of 2% on public liabilities. We also determine θ to establish a steady-state total leverage of 6 for banks and fix ι to yield an annualized steady-state corporate spread of 2.17% . Furthermore, the parameter κ_p matches a Calvo parameter of 0.82, consistent with the values used in NAWM-II.

Then, for the parameters for the Household preferences, we use the consumption utility weight used in Barrage (2020), while the pollution disutility parameter is calculated to match the production damage function (see Appendix B).

Regarding the environmental parameters, we follow Gibson and Heutel (2020) using the same procedure that Ferrari and Nispi Landi (2024) employ.

Table 2: Environmental and Financial Sector Parameters

Parameter	Description	Value	Source
α_0	Pollution disutility parameter	2.5×10^{-4}	Match output damage
D_0	Constant term in damage function	-0.0076	Ferrari and Nispi Landi (2024)
D_1	Linear term in damage function	9.0182×10^{-7}	Ferrari and Nispi Landi (2024)
D_2	Quadratic term in damage function	1.2013×10^{-10}	Ferrari and Nispi Landi (2024)
δ_x	Pollution decay rate	0.0035	Ferrari and Nispi Landi (2024)
e^{row}	Constant emissions level	25.11	Ferrari and Nispi Landi (2024)
λ	Convexity parameter of the emission function	0.4	Ferrari and Nispi Landi (2024)
κ_F	Bank portfolio adjustment cost	10^{-4}	Carattini et al. (2023)
b^*	Steady-state share of banks' green bonds	0.2	Market Neutrality
θ	Divertible portion of assets	0.4474	Match $lev_{ss} = 6$
χ	Banks' survival probability	0.95	Coenen et al. (2018)
ι	Wealth share for new banks	0.0024	Ferrari and Nispi Landi (2024)
ρ_e	Emissions responsiveness in Taylor rule	0.1	Chen et al. (2021)
μ_{ss}	Steady-state central bank bond holdings	1.35%	Ferrari and Nispi Landi (2024)
μ_{gss}	CB share of green bonds	0.2	Market Neutrality

Finally, in line with Carattini et al. (2023), we adopt $\gamma = 2$, signifying that the green and brown goods exhibit imperfect substitutability. We assign a weight of 0.8 to the brown good $\zeta = 0.8$, consistent with Giovanardi et al. (2023).

‘

4 Results

The model is solved using a perfect foresight approach, which assumes that economic agents form rational expectations and fully anticipate future policy changes and economic conditions. This method is advantageous in analyzing transition dynamics following structural policy shifts, such as introducing a carbon tax or implementing quantitative easing policies. By solving the model under perfect foresight, we can capture the adjustment paths of key macroeconomic and financial variables as the economy converges to its new steady-state equilibrium.

One of the primary reasons for using the perfect foresight approach is its ability to provide a global solution to the model, which is essential for accurately simulating the transition to a low-carbon economy. Unlike local solution methods, which approximate the model around a steady state, perfect foresight enables us to track the full nonlinear adjustment path of the economy. This allows us to analyze the interactions between macroeconomic and financial variables over an extended horizon and understand the long-term implications of different policy interventions.

In this framework, the model is expressed as a system of nonlinear equations, which are solved numerically using a deterministic transition path approach. The economy starts from an initial steady state, where all variables are in equilibrium, and then undergoes the imposition of a carbon tax. The model then determines the time path of all endogenous variables, ensuring that intertemporal conditions hold and that the economy eventually reaches a new steady state consistent with the policy change.

The solution method relies on backward-induction algorithms, where agents take into account all available information about the future trajectory of the economy. This allows for a smooth transition, avoiding unrealistic jumps in expectations. We compute the numerical solution using the Levenberg-Marquardt mixed complementarity problem (LMMCP) solver, which is well-suited for handling models with occasionally binding constraints, to account for the zero lower bound on nominal interest rates in our model (Judd, 1998; Kanzow and Petra, 2005).

By using perfect foresight, we eliminate the uncertainty typically associated with stochastic simulations, allowing us to isolate the pure effects of policy interventions. This makes it particularly useful for evaluating long-run policy impacts and understanding how monetary and fiscal instruments interact in transitioning to a low-carbon economy. However, the assumption that agents perfectly anticipate policy changes may understate potential real-world frictions, such as policy uncertainty,

imperfect information, or financial market rigidities, which could slow down the transition dynamics in practice.

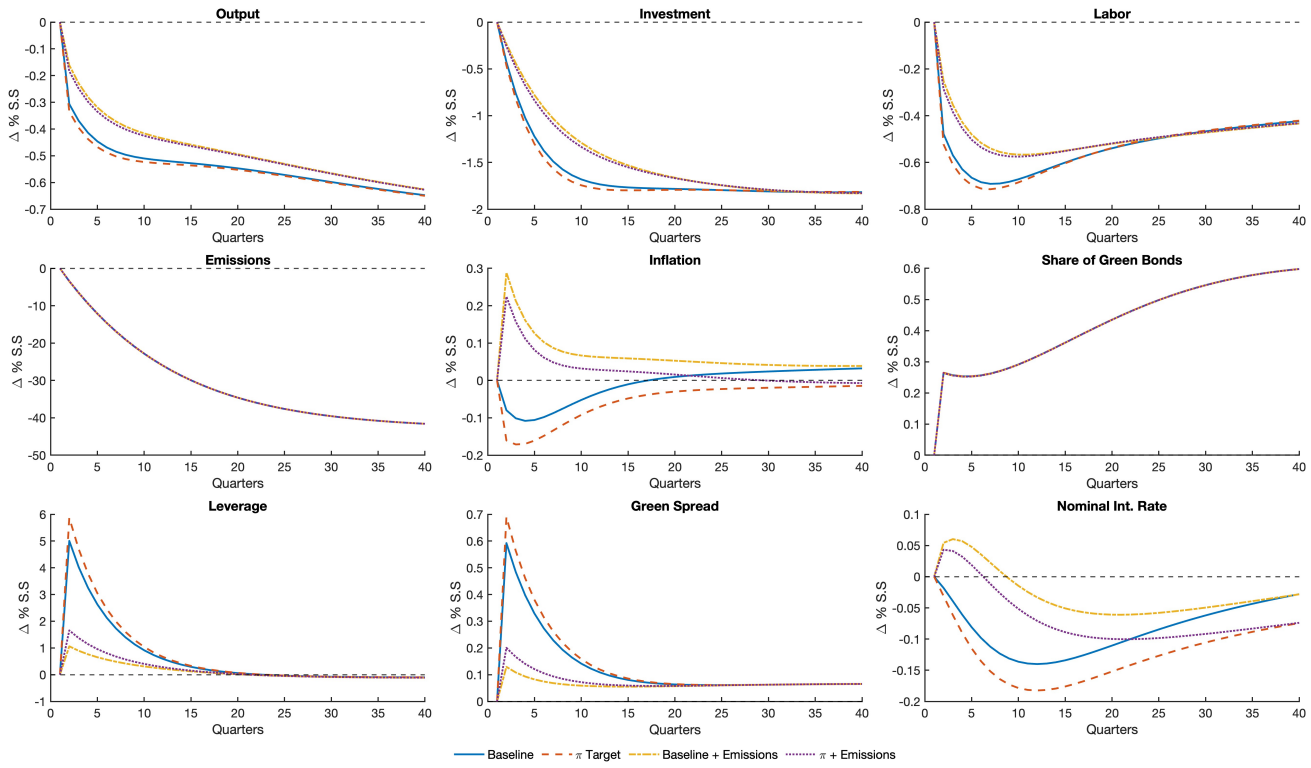
4.1 Monetary Policy - Taylor Rule

The transition to a low-carbon economy presents significant macroeconomic and financial challenges, particularly in the presence of structural adjustments induced by climate policies. The dynamic responses illustrated in Figure 1 exhibit the effects of different Taylor rule specifications on key macroeconomic and financial variables following the introduction of a carbon tax of 18 dollars per ton of Carbon that decreases emissions by 40% from the original Steady State. Meanwhile, the normative analysis in Table 2 evaluates the welfare implications of these monetary policy rules, showing the trade-offs between economic stabilization and financial market adjustments.

In Figure 1, we can observe that the implementation of a carbon tax leads to a contraction in output, investment, and labor, reflecting the adjustment costs associated with the shift away from carbon-intensive production[6]. The contraction in investment is particularly pronounced, consistent with previous findings on the heightened sensitivity of capital formation to policy-induced uncertainty (Hassler et al., 2016). The financial sector also undergoes substantial realignments, with a decline in brown bond issuance and an increase in green bonds, indicating a shift toward sustainable assets. However, the transition is not without friction, as evidenced by the temporary spike in green spreads and leverage, suggesting a heightened financial risk in the short run before stabilization occurs.

[6]We present the complete set of figures in Appendix D

Figure 1: Transition to a Low Carbon Economy - Conventional MP



In the context of the standard Taylor rule, the economy experiences a sharp contraction in output, investment, and labor, reflecting the transition costs associated with carbon pricing. Inflation initially declines but recovers gradually, with different policy rules affecting the speed and extent of this adjustment. Monetary policies incorporating an explicit emissions target allow for greater counter-cyclical support, resulting in a smaller output decline and a smoother investment response. Inflation-targeting policies, on the other hand, prioritize price stability but at the cost of greater output volatility and decline, these results being consistent with those in McKibbin et al. (2020). Financial market responses also differ: leverage rises before stabilizing, while the green spread spikes as capital reallocates toward green investment. Policies that include an emissions target moderate financial volatility and facilitate a more gradual transition, supporting the growth of green bonds while limiting excessive fluctuations in credit conditions.

The analysis in Table 2 exhibit the trade-offs between economic stabilization and financial adjustments. Strict inflation targeting results in a small welfare loss, as it amplifies the decline in output while providing only marginal additional reductions in emissions. In contrast, rules incorporating emissions targets generate positive welfare effects, with the Baseline + Emission Targeting rule delivering the highest welfare gain. This implies that monetary policy can improve economic outcomes by

accounting for emissions dynamics, helping mitigate the transition's short-term costs. While inflation-targeting rules achieve lower central bank losses, they do so at the cost of greater macroeconomic volatility.

Table 3: Normative Analysis - Taylor Rule

Policy	Δ Welfare	Δ Output	Δ Emissions	Δ CB Loss Function
Baseline Taylor Rule	-	-	-	-
Inflation Target	-0.0002	-0.0049	-0.0033	-0.0275
Baseline + Emission Target	0.0019	0.0024	0.0209	0.0007
Inflation + Emission Target	0.0018	-0.0022	0.0186	-0.0267

Note: Δ Welfare,Output, Emissions CB Loss Function in % in relation to the baseline Taylor Rule

These findings have important implications for the design of monetary policies in the context of climate transition risks. Integrating emission considerations into monetary policy frameworks improves climate transition policies' effectiveness, helping balance environmental objectives with economic stability. Central banks, particularly in economies exposed to significant climate risks, may benefit from a more flexible approach that supports the transition without undermining core macroeconomic goals.

These results contribute to the debate on the role of central banks in climate policy, challenging the view that monetary authorities should focus solely on macroeconomic and financial stability while leaving explicit climate mitigation efforts to fiscal and regulatory policies (Schnabel, 2022).

We argue that monetary policy plays a critical role in shaping the economic and financial trajectory of the transition to a low-carbon economy. While it cannot replace fiscal and regulatory tools, its ability to mitigate transition risks and stabilize financial markets suggests that it should be an integral part of the broader policy mix. These argue for the need for a coordinated strategy that combines monetary, fiscal, and financial regulation policies to manage the complexities of the green transition.

4.2 Unconventional Monetary Policy - Quantitative Easing

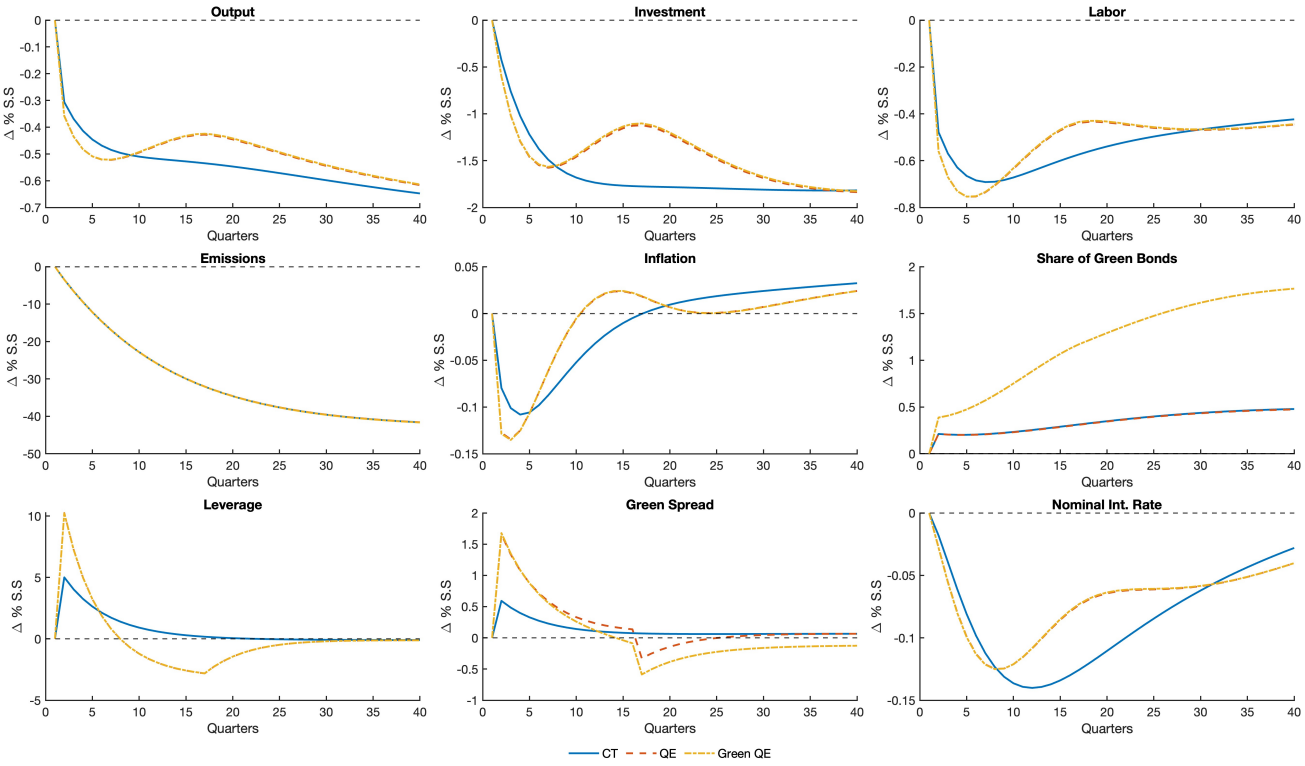
4.2.1 Deterministic Transition Risk - Carbon Tax

In this scenario, we evaluate the performance of different Quantitative Easing (QE) policies during the transition to a low-carbon economy, applying the same carbon tax magnitude as in Section 3.1.1. Specifically, we examine the differences between a market-neutral QE program and a green-biased QE initiative in response to the economic decline accompanying the transition to a new steady state.

While Gertler and Karadi (2011) originally proposed QE as a response to financial crises, here we consider its role in mitigating the economic downturn caused by higher intermediate brown goods prices and a decline in brown-sector output, which is not fully offset by growth in the green sector. Given these dynamics, QE may serve as a valuable tool in addressing the recessionary pressures of the transition.

We begin by analyzing the role of the central bank's asset purchase program in both a permanent and transitory setting. In the permanent scenario, we compare two policy approaches: (i) a market-neutral QE, where the central bank gradually increases the share of public bonds in its portfolio by two percentage points while maintaining the existing composition of brown and green assets in the economy, and (ii) a green-biased QE initiative, where the same increase in public bond holdings is accompanied by a 20 percentage point increase in the share of green assets held by the central bank, thus departing from market neutrality. By contrasting these approaches, we assess how a QE policy can facilitate the transition to a low-carbon economy while stabilizing macroeconomic conditions.

Figure 2: Transition to a Low Carbon Economy - Permanent Quantitative Easing



The results highlight the distinct macroeconomic and financial effects of neutral and green-biased quantitative easing (QE) policies during the transition to a low-carbon economy. Both QE policies help cushion the contractionary impact of the carbon tax by stabilizing output and investment. However,

Green QE is more effective in boosting investment and promoting a faster recovery. Leverage initially rises under both policies, reflecting improved credit conditions, but stabilizes over time. In particular, green QE leads to a more considerable reduction in the green spread, indicating improved financing conditions for environmentally friendly projects.

Table 4: Normative Analysis - Permanent Quantitative Easing

Policy	Δ Welfare	Δ Output	Δ Emissions	Δ CB Loss Function
Carbon Tax	-	-	-	-
Neutral QE	0.0069	0.0236	0.0128	-0.0072
Green QE	0.0101	0.0262	-0.0678	-0.0082

Note: Δ Welfare,Output, Emissions CB Loss Function in % in relation to the Carbon Tax scenario

The normative analysis further supports these findings. Both QE policies enhance welfare and output relative to the carbon tax scenario, but Green QE provides the greatest benefits. A key distinction lies in emissions: while Neutral QE results in a slight increase, Green QE achieves a meaningful reduction, aligning financial markets more closely with climate policy goals. Additionally, Green QE contributes to a lower central bank loss function, indicating improved overall economic stability. These results suggest that while QE generally can support the transition, a targeted green-biased approach is more effective in promoting both economic recovery and environmental sustainability.

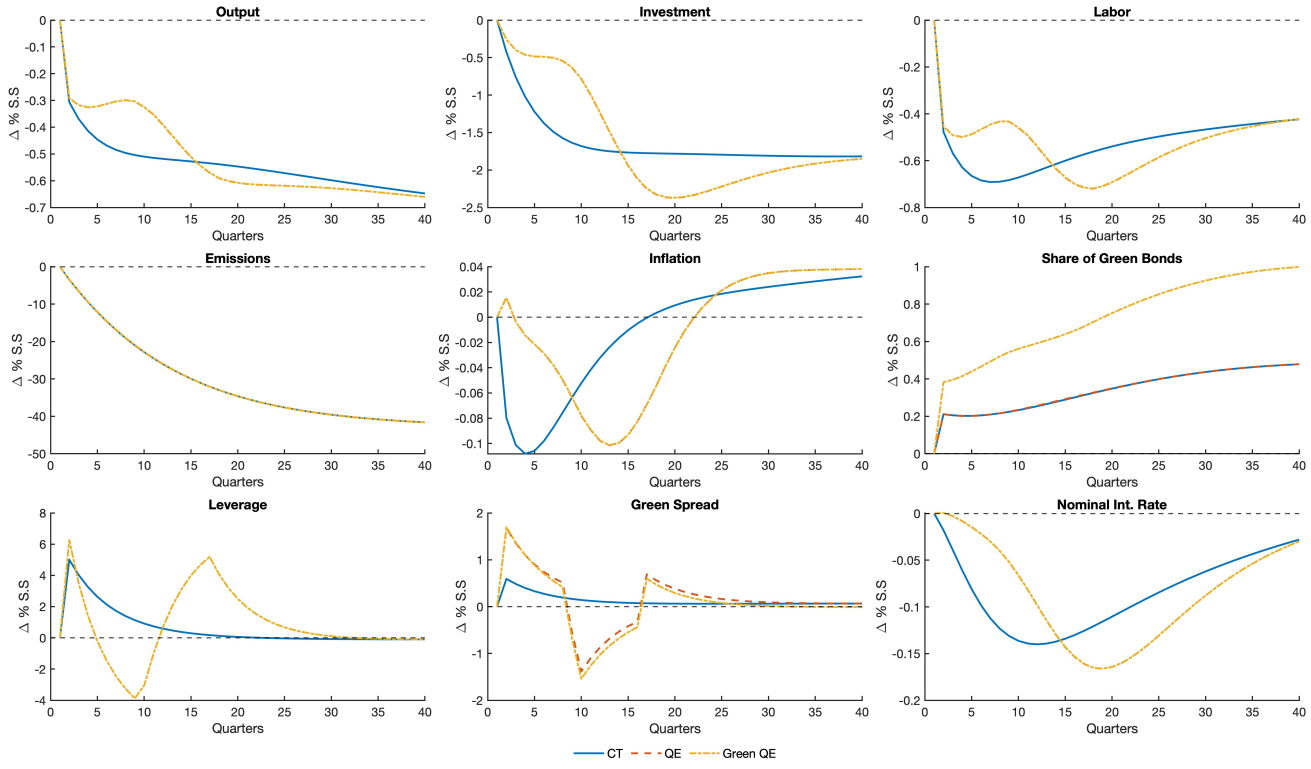
Expanding the analysis to include a temporary QE program, we simulate a gradual increase in asset purchases over eight periods, reaching a peak of two percentage points (the same magnitude as in the permanent case), followed by a symmetric reduction over the subsequent eight periods, returning to the original share of public bonds. This ensures that the total scale of the asset purchase program remains consistent with the permanent intervention but is implemented over a four-year horizon.

For the Green Quantitative Easing scenario, we assume that the central bank gradually increases its share of green bond holdings over 16 periods and then maintains that level permanently. Unlike the neutral QE case, where the total stock of public bonds eventually returns to its steady-state level, this policy alters the composition of the central bank's portfolio, favoring green assets while reducing the share of brown bonds.

Figure 3 illustrates the results of this exercise, showing that despite its temporary nature, the QE program can still partially mitigate economic instability during the transition to a low-carbon econ-

omy. The overall effects remain qualitatively similar to the permanent QE intervention, suggesting that even a transitory adjustment in monetary policy can help smooth the adjustment path, supporting investment and reducing the adverse macroeconomic consequences of the transition. However, the permanence of the green QE component can argue in favor the potential role of central banks in influencing capital allocation toward sustainable assets beyond short-term stabilization objectives.

Figure 3: Transition to a Low Carbon Economy - Temporary Quantitative Easing



The temporary QE program results suggest that while Neutral and Green QE provide some output stabilization during the transition, their overall effects are more limited compared to the permanent intervention. Neutral QE leads to a modest increase in output but is associated with a slight decline in welfare, indicating that its benefits may not fully offset its costs. On the other hand, Green QE results in a small welfare gain and a notable reduction in emissions, suggesting that adjustments in the central bank's asset composition can contribute to the transition to a low-carbon economy. However, both policies lead to a marginal increase in the central bank's loss function, indicating some trade-offs between economic stabilization and financial market adjustments. These findings indicate that while temporary QE can help mitigate some of the transition effects, its impact remains more constrained than a permanent intervention.

Table 5: Normative Analysis - Temporary Quantitative Easing

Policy	Δ Welfare	Δ Output	Δ Emissions	Δ CB Loss Function
Carbon Tax	-	-	-	-
Neutral QE	-0.0029	0.0052	0.0055	0.0034
Green QE	0.0080	0.0052	-0.0280	0.0034

Note: Δ Welfare,Output, Emissions CB Loss Function in % in relation to the Carbon Tax scenario

These findings carry important policy implications for central banks navigating the transition to a low-carbon economy. The ability of QE to mitigate the contractionary effects of a carbon tax suggests that monetary policy can play a complementary role in facilitating a smoother economic adjustment. However, the differential impact between Neutral and Green QE shows the importance of the design of such interventions. A market-neutral approach stabilizes output but does little to redirect financial flows toward green investments. In contrast, a green-biased approach not only supports economic activity but also reinforces the transition's environmental objectives.

From a financial stability perspective, the results suggest that Green QE could help reduce the cost of financing for green projects, potentially accelerating the shift away from carbon-intensive production. By lowering the green spread and supporting the issuance of green bonds, the central bank can enhance market incentives for firms to invest in sustainable technologies. This aligns monetary policy with broader climate transition goals without undermining macroeconomic stability.

4.3 Model Validation

We evaluate the performance of the baseline model by comparing its predictions to untargeted moments in business cycle dynamics and greenhouse gas emissions. This validation step is essential to assess the model's empirical relevance and ability to replicate key macroeconomic and environmental patterns observed in the data.

To compute business cycle statistics, we simulate the model over 1,000 periods and discard the initial 100 observations to eliminate transient dynamics and ensure that the results reflect the stationary distribution of the model. Moments are then computed using the remaining 900 periods. We focus on macroeconomic aggregates' volatility, persistence, and co-movement, particularly output, consumption, and investment.

For empirical validation, we use quarterly data from Eurostat for the Euro Area (20 countries) covering the period from 1995Q1 to 2023Q2. This dataset provides real GDP, total investment, and private

consumption, which serve as key benchmarks for evaluating the model's macroeconomic predictions. To assess the model's ability to capture emissions dynamics, we rely on quarterly total greenhouse gas emissions data available from 2010Q1 to 2023Q1.

Table 2 compares the model's simulated moments and empirical counterparts, presenting its ability to replicate key business cycle properties and emissions characteristics. The model successfully captures the relative volatility of consumption and investment compared to output, with standard deviation ratios closely matching observed data.

Table 6: Model Validation

Variable (x) (y=output)	Data		Model	
	$\sigma(x)/\sigma(y)$	$\rho(x,y)$	$\sigma(x)/\sigma(y)$	$\rho(x,y)$
Consumption	1.022	0.97	1.115	0.96
Investment	1.751	0.79	2.275	0.88
Emissions	2.28	0.75	0.76	0.91

However, when examining greenhouse gas emissions, the model underestimates their volatility relative to output compared to empirical data. This discrepancy may stem from differences in measurement: the Eurostat dataset includes multiple greenhouse gases (expressed in CO2 equivalents), whereas our model focuses exclusively on Carbon emissions. Despite this limitation, the model effectively captures emissions' procyclical behavior, as reflected in its high correlation with output.

Despite these differences, the model captures the overall trends and associations well. Specifically, our model demonstrates similar correlations with the actual data for all variables, indicating a robust alignment between our model's predictions and observed real-world patterns.

4.4 Robustness Checks

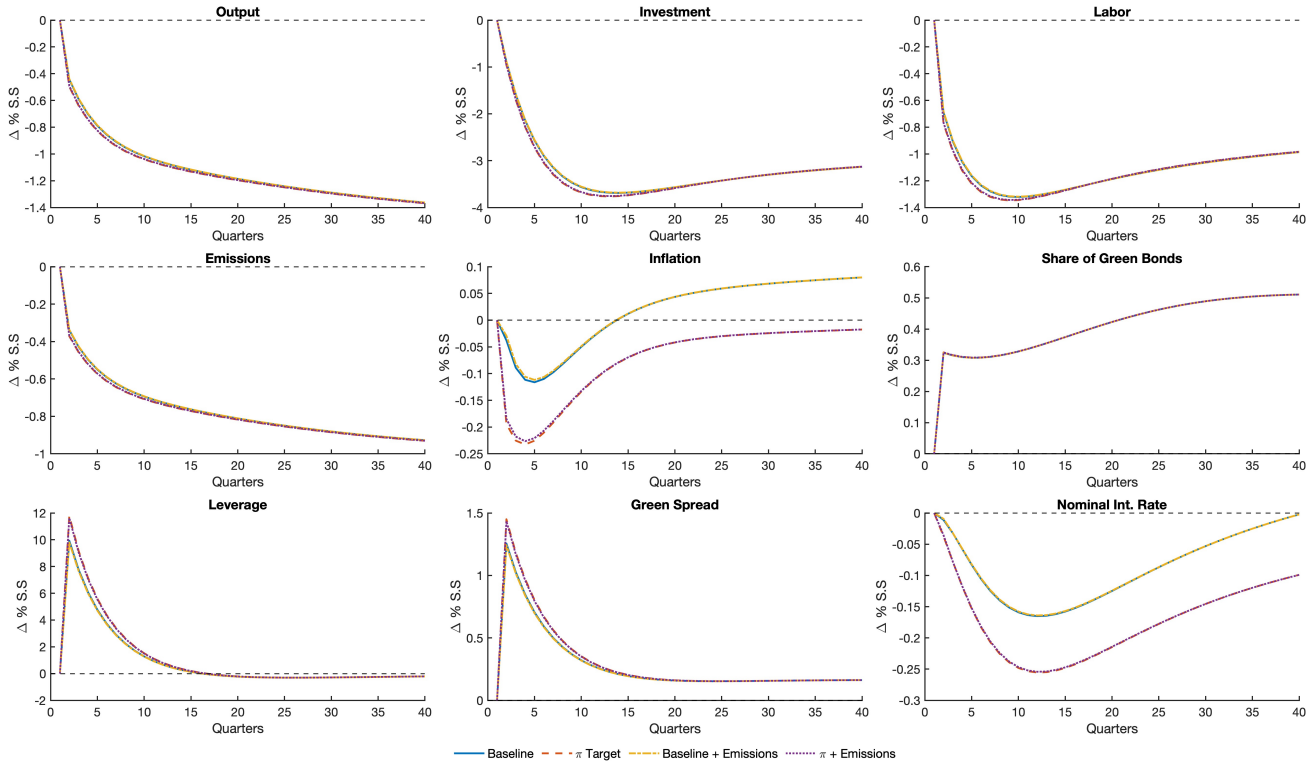
The robustness analysis (full details in Appendix E) examines the model's sensitivity to an alternative emissions specification by removing abatement technology, making emissions a direct function of brown sector production. This adjustment isolates the relationship between brown output and emissions, eliminating the mitigating role of endogenous abatement responses.

This modification allows us to evaluate the extent to which abatement technology influences the transition dynamics and the macroeconomic implications of climate policies. Under this alternative setup, emission responds passively to changes in brown sector activity rather than being actively managed through abatement efforts.

The results, presented in Figures 4 and 5, show that the decline in emissions following a carbon

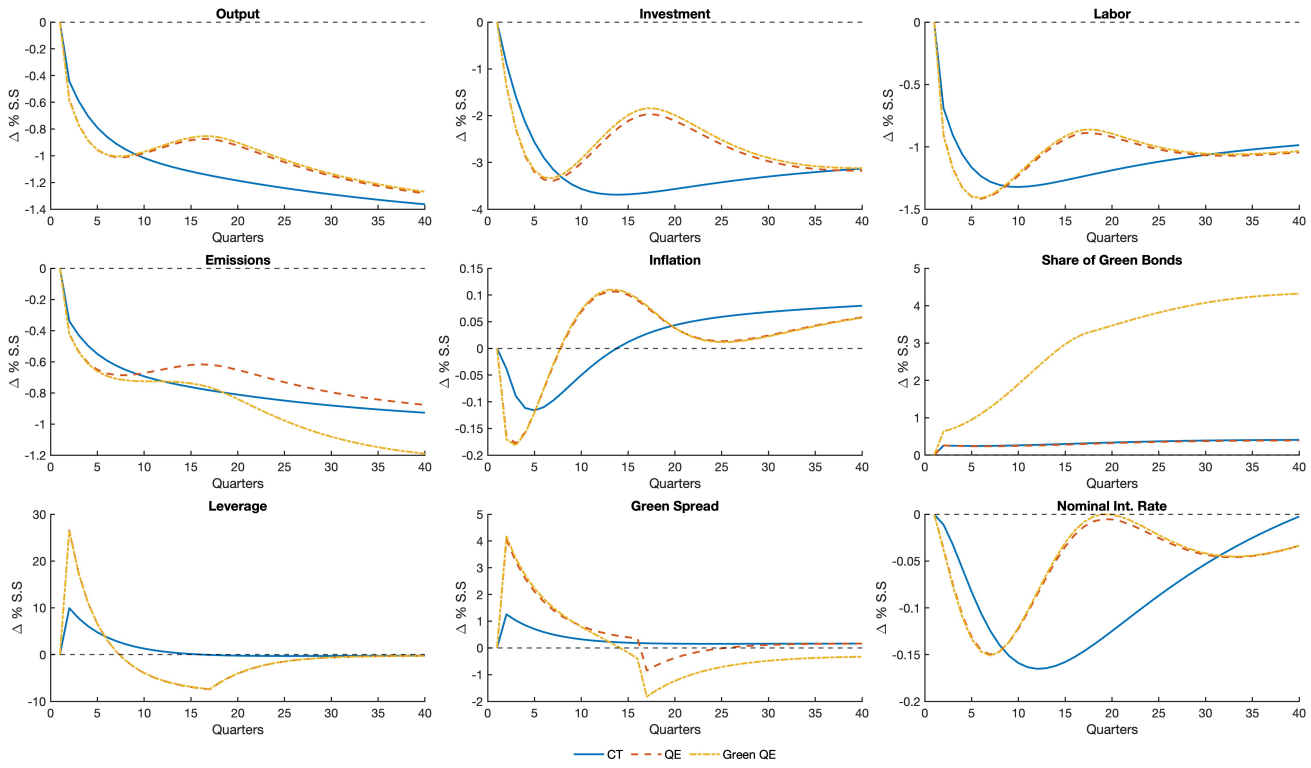
tax is more pronounced without abatement, as firms cannot adjust emissions independently from output. Consequently, the brown sector's contraction directly translates into emissions reductions, making emissions responses more rigid compared to the baseline case. However, key macroeconomic variables, including output, investment, and labor, remain broadly consistent with the baseline results, confirming the robustness of the model's broader dynamics.

Figure 4: Transition to a Low Carbon Economy - Conventional MP



Examining the Taylor Rule under both specifications show differences in the macroeconomic and welfare outcomes of monetary policy responses to the carbon tax. When abatement technology is present, incorporating an emissions target into the Taylor Rule improves welfare while only marginally affecting output, leading to a meaningful reduction in emissions. In contrast, an inflation-targeting rule results in slight welfare losses and a moderate output contraction while having a limited effect on emissions. Without abatement, economic trade-offs become more pronounced—inflation targeting leads to a sharper decline in output and a larger welfare loss, reflecting the higher costs of emissions reductions when firms cannot abate emissions. Even with an emissions target, the Taylor Rule yields a more pronounced welfare gain, though it does not significantly enhance emissions reductions.

Figure 5: Transition to a Low Carbon Economy - Permanent Quantitative Easing



Comparing permanent Quantitative Easing (QE) across the two specifications reveals substantial differences in its effectiveness. With abatement technology, both Neutral and Green QE improve welfare and output relative to the carbon tax scenario, with Green QE providing the highest welfare gains and the strongest emissions reductions. Neutral QE, conversely, results in a moderate emissions increase. In both cases, the reduction in the Central Bank Loss Function suggests that QE interventions help stabilize macroeconomic conditions during the transition.

Without abatement, the effects of QE are amplified—welfare gains and output expansion are more considerable, reflecting the heightened economic costs of the carbon tax. Green QE leads to a much steeper decline in emissions, while Neutral QE continues to generate an emissions increase, albeit more substantial than in the abatement case. These results argue the role of Green QE in redirecting capital away from brown sectors, particularly in scenarios where firms lack the ability to reduce emissions through technological improvements.

From a policy perspective, these findings emphasize the critical role of abatement technology in mitigating the economic costs of emission reductions. Without it, the trade-offs between output stabilization and emissions control are steeper, making monetary policy interventions less effective in smoothing the transition. Central banks may be better positioned to support a low-carbon transi-

tion when abatement policies are in place, as they facilitate emission reductions with less economic disruption. Furthermore, Green QE can serve as a powerful tool in shifting financial flows toward sustainable investments, particularly in the absence of abatement, reinforcing the importance of aligning monetary policy with climate objectives.

5 Optimal Policy Analysis

5.1 Unconventional Monetary policy

To assess the welfare implications of introducing Quantitative Easing (QE) alongside a Carbon Tax, we compute welfare in certainty equivalent (CE) consumption units. We compare the transition path to the new low-carbon steady state, using as a baseline scenario the Carbon Tax alone and comparing it with the change in the share of different values of Public Bonds (μ_t) and the share of green bonds ($\mu_{g,t}$) in Central Bank holdings.

In doing so, we compute the Certainty Equivalence of Welfare relative to the scenario with only the Carbon Tax, against the different QE rules, for various values of the intensity of the policy.

The Epstein-Zin recursive utility function gives the representative agent's lifetime utility:

$$V_t = \left\{ (1-\beta) \left[\left(C_t^{\omega} (1-L_t)^{1-\omega} \right)^{1-\frac{1}{\psi}} - (\alpha_0 X_t)^{1-\frac{1}{\psi}} \right] + \beta \mathbb{E}_t \left(V_{t+1}^{1-\gamma} \right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right\}^{\frac{1}{1-\frac{1}{\psi}}} \tag{24}$$

To quantify the welfare impact of QE, we compute the percentage change in certainty equivalent consumption relative to the Carbon Tax Only scenario:

$$\text{Welfare Gain} = \left(\frac{\bar{C}^{\text{Tax+QE}}}{\bar{C}^{\text{Tax}}} - 1 \right) \times 100. \tag{25}$$

In this context, we have a Carbon-Tax only scenario, a Carbon Tax, and a QE program with different intensities. Here, we define $\mathbb{E}[V_0^{CT}]$ and $\mathbb{E}[V_0^{CT+QE}]$ be their respective expected lifetime EZ utilities at time 0. The consumption-equivalent gain λ is defined via

$$V_0^{CT}(\lambda) \;=\; V_0^{CT+QE},$$

where $V_0^{CT}(\lambda)$ denotes the EZ value in regime CT if its consumption path is scaled by $(1+\lambda)$ at each date.

To compute λ, we rely on non-linear methods via root-finding on $F(\lambda) = V_0^{CT}(\lambda) - V_0^{CT+QE} = 0$. Scaling $(1+\lambda)$ is applied only to consumption in scenario CT, while labor and pollution remain unchanged, thus identifying how much consumption adjustment is needed for equivalence to scenario $CT + QE$.

We use the following algorithm to solve for the Welfare Gains in Consumption Equivalence Units:

1. Solve or simulate each policy regime (CT and $CT + QE$) to obtain paths $\{C_t,\, L_t,\, X_t\}$.
2. Compute V_0^{Ct+QE} by applying the EZ recursion in regime $CT + QE$.
3. Define $F(\lambda) = V_0^{CT}(\lambda) - V_0^{CT+QE}$, where $V_0^{CT}(\lambda)$ is computed by substituting $(1+\lambda)\, C_t^{CT}$ into the aggregator each period.
4. Use a root-finder to find λ^* such that $F(\lambda^*) = 0$.

An additional dimension of our analysis examines the role of Quantitative Easing (QE) in stabilizing macroeconomic dynamics. To quantify its impact, we use the Central Bank Loss Function (CBLF) to measure macroeconomic volatility, capturing deviations from key monetary policy targets such as inflation, output, and interest rate fluctuations. By comparing the mean loss function between the Carbon Tax-only and QE-augmented scenarios, we assess whether QE helps reduce policy distortions or exacerbates macroeconomic instability:

$$\Delta Loss_t^{CB} = \left(\frac{\text{Mean } Loss_t^{CB}\text{QE + Tax}}{\text{Mean } Loss_t^{CB}\text{Tax}} - 1 \right) \times 100. \tag{26}$$

Since emissions reduction is also a key objective, we evaluate the mean emissions reduction in each scenario relative to the Carbon Tax-only case. This allows us to determine which QE profile, if any, enhances emissions reductions:

$$\Delta emissions_t = \left(\frac{\text{Mean } e_t^{\text{QE + Tax}}}{\text{Mean } e_t^{\text{Tax}}} - 1 \right) \times 100. \tag{27}$$

By jointly analyzing welfare, macroeconomic stability, and emissions reductions, we provide an assessment of QE's effectiveness. First, we evaluate its impact on long-term welfare in consumption-equivalent terms; second, we assess its role in short- and medium-term macroeconomic stability; and third, we examine its ability to accelerate climate transition goals. If an optimal QE profile consistently enhances all three dimensions, it could serve as a viable complementary policy tool alongside carbon taxation.

In the following subsection, we show the optimal combination of μ_t and $\mu_{g,t}$ for each individual objective.

5.1.1 Optimal Quantitative Easing

In this analysis, we examine welfare changes, the Central Bank Loss Function (CBLF), and emissions variations under different realistic scenarios for the share of public bonds held by the central bank (μ_t) and the proportion of green bonds in its portfolio ($\mu_{g,t}$). We assume that the maximum share of total bonds the central bank can hold is four percentage points above the steady-state level of a carbon-intensive economy, setting an upper bound of $\mu_t^{\max} = 5.35\%$. Additionally, we impose a constraint on the green bond share, ensuring that it does not exceed 50% of the banking sector's total bond holdings ($\mu_{g,t}^{\max} = 50\%$). These constraints reflect practical limitations on central bank intervention while allowing us to assess the trade-offs between macroeconomic stability, welfare improvements, and emissions reduction in designing an optimal Quantitative Easing (QE) strategy during the green transition.

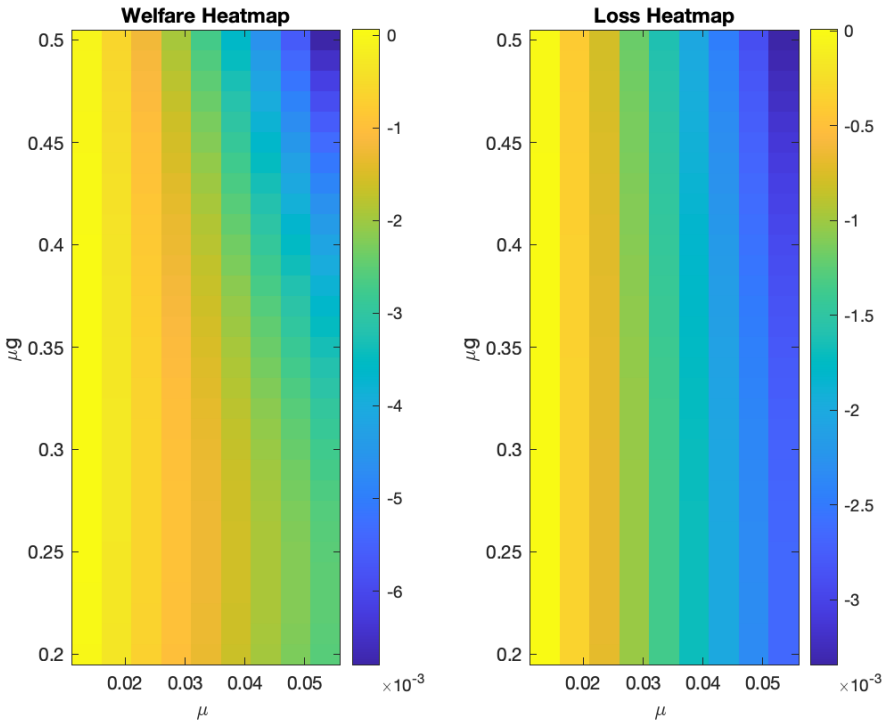
Table 7: Optimal Quantitative Easing

Quantitative Easing	**Values**	**ΔWelfare (%CE)**	**ΔCB Loss Function(%)**	**Δ Emissions (%)**
Max Welfare	$\mu = 0.0135$, $\mu_G = 0.32$	0.0001	0.0001	-0.0198
Min CBLF	$\mu = 0.0535$, $\mu_G = 0.50$	-0.0068	-0.0033	-0.1456
0.5 Welfare + 0.5 CBLF	$\mu = 0.0335$, $\mu_G = 0.41$	-0.0019	-0.0015	-0.0639

Table 7 and Figure 6 results shows the trade-offs between welfare maximization, macroeconomic stability, and emissions reduction. Increasing the share of green bonds (μ_G) in the central bank's portfolio influences these objectives differently depending on the policy focus. A welfare-maximizing strategy, which prioritizes green asset purchases, is associated with greater welfare gains but also leads to lower emissions reduction, suggesting that a more accommodative monetary stance supports economic activity while indirectly affecting emissions. In contrast, a stability-oriented QE policy, which minimizes the CBLF, is associated with lower macroeconomic volatility and a higher reduction in emissions, reinforcing the idea that financial stability measures can indirectly support the transition by tightening financial conditions for carbon-intensive industries. A balanced approach, which considers both welfare and stability objectives, provides an intermediate solution, improving welfare while achieving moderate emissions reductions and keeping macroeconomic distortions contained.

A key takeaway is that QE interventions influence emissions indirectly through financial conditions, credit allocation and economic activity, rather than as an explicit monetary policy objective. While stabilization-focused QE policies tend to reduce emissions, those aimed at welfare improvements stimulate economic expansion, potentially delaying emissions reductions. This suggests that even when operating within their traditional mandates, central banks can still influence environmental outcomes through the design of QE strategies. We acknowledge that implementing Green QE would require deviating from the assumption of market neutrality. Nevertheless, Papoutsi et al. (2021) demonstrates that the European Central Bank's (ECB) asset portfolio is already skewed toward carbon-intensive sectors, suggesting that, in practice, market neutrality is not strictly upheld. This implies that a shift toward Green QE would not necessarily introduce new distortions but could help correct existing biases in central bank asset purchases.

Figure 6: Welfare Gains and Loss Function

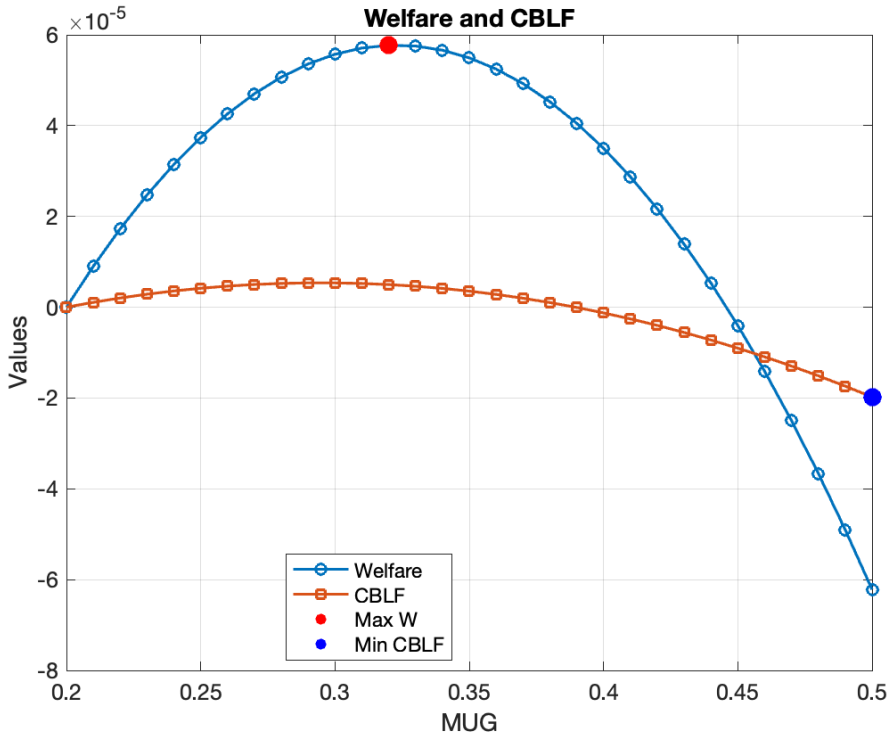


From a policy perspective, these findings reinforce the notion that QE should primarily serve as a tool for macroeconomic stability, with emissions impacts emerging as secondary effects rather than direct policy targets. The CBLF-minimizing approach aligns most closely with central banks' mandates, as it ensures macroeconomic stability while indirectly contributing to emissions reductions. An optimal QE framework during the transition should strike a balance between stability and welfare

objectives, ensuring that monetary interventions remain effective without distorting financial markets or overstepping fiscal policy.

Even when the central bank's total bond holdings remain unchanged ($\mu_t = 0$), the optimal share of green bonds exceeds the market neutrality benchmark of 20%, reaching approximately 32% (Figure 7). Hence, proactively reallocating the bond portfolio (purchasing green bonds while selling brown ones) can improve welfare.

Figure 7: Welfare Gains and Loss Function - $\mu_t = 0$



Furthermore, as the share of green bonds ($\mu_{g,t}$) increases, the Central Bank Loss Function (CBLF) steadily declines, meaning that higher green bond purchases contribute to reducing macroeconomic volatility. However, this relationship is nonlinear: exceeding the welfare-maximizing level of green bond allocation leads to diminishing welfare gains, even as the CBLF improves. This divergence implies that while welfare maximization and macroeconomic stability are partially aligned, they do not coincide at the same level of ($\mu_{g,t}$), necessitating a trade-off in designing an optimal QE strategy.

Here, we emphasize that central bank interventions through green QE can enhance welfare and improve macroeconomic stability, even without expanding the total bond portfolio. However, the optimal design of such policies requires careful calibration to balance welfare gains and stability objectives, ensuring that monetary interventions support the green transition without introducing unin-

tended distortions.

5.2 Conventional Monetary policy - Optimal Taylor Rule

While unconventional monetary policies such as Quantitative Easing (QE) offer potential tools to support the transition to a low-carbon economy, conventional monetary policy remains a fundamental instrument for macroeconomic stabilization. In this section, we aim to compute the optimal Taylor Rule during the green transition, using a Taylor Rule with pure inflation targeting and interest rate smoothing as a benchmark.

The inclusion of ρ_e in equation 20 introduces an emissions objective into the central bank's reaction function, aligning with recent discussions on incorporating environmental considerations into monetary policy, mainly as climate-related risks increasingly influence macroeconomic conditions (Chen et al., 2021). To assess the implications of an emissions-sensitive Taylor Rule, we simulate the transition path to the low-carbon steady state under varying degrees of central bank responsiveness to emissions (ρ_e) and the output gap (ρ_y). We then evaluate welfare gains (or losses) relative to the inflation-targeting rule (i.e., $\rho_y = \rho_e = 0$), the Central Bank Loss Function (CBLF), and the overall effectiveness in reducing emissions.

The emissions-augmented Taylor Rule presents a fundamental trade-off between macroeconomic stability and climate objectives. While a higher emissions responsiveness (ρ_e) allows monetary policy to curb carbon-intensive economic activity by adjusting interest rates, it may also increase inflation and output volatility. However, in a low-carbon transition driven by active fiscal climate policies, central banks may opt to ease interest rates in response to an economic slowdown, prioritizing short-term stability at the cost of a slower emissions reduction. In our specification of the augmented Taylor rule, an overly aggressive emissions response could result in pro-cyclical monetary policy, amplifying economic downturns rather than stabilizing them.

Similarly, the Taylor Rule's output gap responsiveness (ρ_y) plays a crucial role in shaping this trade-off. A higher ρ_y strengthens monetary policy's countercyclical function by responding more aggressively to output fluctuations, helping cushion carbon taxation's economic costs. However, excessive output stabilization may dampen the effectiveness of emissions-reducing fiscal policies, as monetary easing could inadvertently support carbon-intensive production. Thus, the interplay between ρ_e (emissions targeting) and ρ_y (output gap responsiveness) is critical in determining the overall effectiveness and stability of an emissions-augmented Taylor Rule.

Appropriate calibration of ρ_e and ρ_y is essential to ensure a balanced policy response. A moderate emissions response could enhance fiscal climate policies by aligning monetary incentives with carbon taxation, while avoiding excessive macroeconomic instability. Conversely, an overly strong emissions focus may introduce undesirable volatility, focus in the need for careful monetary-fiscal coordination to maintain both price stability and environmental objectives.

5.2.1 Optimal Taylor Rule

Analyzing the optimal Taylor Rule parameters during the green transition exhibit the fundamental trade-offs between welfare, macroeconomic stability, and emissions reduction. The choice of output gap responsiveness (ϕ_y) and emissions responsiveness (ϕ_e) determines the central bank's ability to support the transition while maintaining its primary mandates of price stability and economic stability.

The results in Table 8 indicate that a higher response to emissions (ϕ_e) tends to increase welfare. However, this comes at the cost of higher macroeconomic volatility, as reflected in the Central Bank Loss Function (CBLF), and decreases the effectiveness of emissions-reducing fiscal measures. A higher output gap responsiveness (ϕ_y) strengthens monetary policy's countercyclical function, mitigating output fluctuations and minimizing policy distortions. This suggests that monetary policy can complement but not substitute fiscal climate policies, as excessive monetary accommodation may inadvertently support carbon-intensive production.

Table 8: Optimal Parameters for Taylor Rule

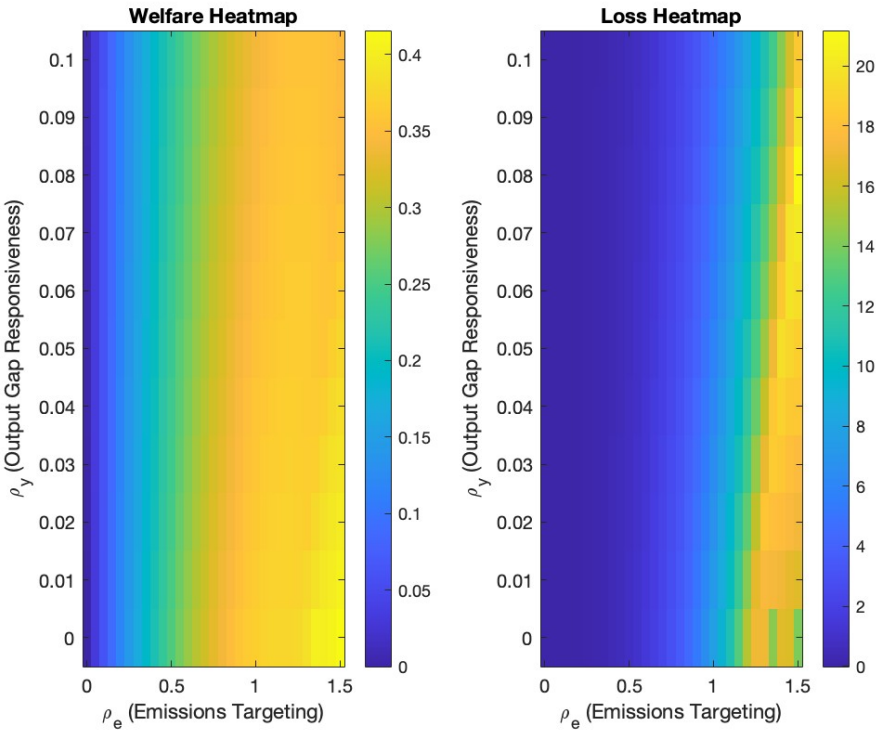
Taylor Rule Scenario	**Parameter Values**	**ΔWelfare (%CE)**	**ΔCB Loss Function(%)**	**Δ Emissions (%)**
Standard	$\phi_y = 0.03, \phi_e = 0$	0.0025	-0.0000	0.0033
Max Welfare	$\phi_y = 0, \phi_e = 1.5$	0.4157	0.2244	10.96
Min CBLF	$\phi_y = 0.01, \phi_e = 0.05$	0.0321	-0.0001	0.0370
0.5 Welfare + 0.5 CBLF	$\phi_y = 0.005, \phi_e = 0.775$	0.3397	0.0582	0.6156

A key takeaway from this analysis is the nonlinear relationship between emissions targeting and macroeconomic stability (Figure 8). While a moderate emissions response (ϕ_e) can align monetary incentives with carbon taxation, an overly strong emissions focus can amplify policy distortions.

In this context, the optimal design of the Taylor Rule must balance the economic benefits of emissions targeting with the risks of increased monetary instability. An approach where the central bank

focuses on its dual mandate appears to be the most effective, as the Taylor Rule that minimizes the loss function also yields welfare gains relative to the standard Taylor Rule and the pure inflation-targeting Taylor Rule, while keeping emissions increases at manageable levels. While the inflation-targeting Taylor Rule ignores transition-related trade-offs, and the max-welfare rule introduces significant instability, the loss function approach provides an optimal compromise, increasing welfare gains relative to standard and inflation target rules without inducing excessive macroeconomic volatility.

Figure 8: Welfare Gains and Loss Function



The findings emphasize that central banks should carefully calibrate their monetary policy responses to complement fiscal climate policies while avoiding excessive trade-offs between welfare and macroeconomic stability. Surprisingly, this optimal approach incorporates a low emissions response (ϕ_e) into the Taylor Rule, demonstrating that when appropriately designed, monetary policy can indirectly complement fiscal climate interventions. Notably, while emissions may increase slightly under this rule compared to other policies, they remain manageable. This indicates that the macroeconomic benefits of stability outweigh the minor trade-offs in emissions reduction without compromising the emission reductions achieved through fiscal policy.

Here, we challenge the notion that central banks must choose between stability and environmental objectives. Instead, it suggests that a well-calibrated Taylor Rule focused on macroeconomic stability

naturally incorporates an emissions target, allowing for a policy framework that aligns with fiscal climate policies while preserving the credibility and effectiveness of monetary policy. By adopting a monetary strategy that prioritizes the minimization of loss functions, central banks can effectively help the economy navigate the transition to a low-carbon economy without compromising their traditional mandate of price stability and economic stabilization.

However, this approach is only valid during the transition to a low-carbon economy. In normal times, central banks should adhere to their traditional mandate of price stability and economic stabilization. Here, fiscal climate policy drives the transition, inducing temporary macroeconomic instability, allowing monetary policy to adjust without compromising emissions reductions. However, if instability arises from a financial crisis or other shocks, the standard Taylor Rule should be applied, as monetary policy must focus solely on stabilization rather than emissions. Thus, while an emissions-augmented Taylor Rule can provide short-term flexibility, central banks should revert to their traditional framework once the transition stabilizes, ensuring their focus remains on economic and financial stability while leaving climate objectives to fiscal authorities.

6 Conclusions

The transition to a low-carbon economy introduces significant macroeconomic and financial stability challenges, requiring a coordinated policy response. Using a two-sector Environmental Dynamic Stochastic General Equilibrium (E-DSGE) model with financial frictions and Epstein-Zin preferences, this study examines how conventional and unconventional monetary policies can mitigate transition risks triggered by a carbon tax. Our findings highlight the complementary role of monetary policy alongside fiscal climate measures, emphasizing the need for carefully designed interventions to balance economic stability, welfare, and environmental objectives.

Conventional monetary policy can amplify output volatility during the transition when focused solely on inflation stabilization. In contrast, an emissions-augmented Taylor Rule, incorporating a moderate response to emissions growth, provides countercyclical support, reducing macroeconomic volatility and enhancing welfare compared to a standard Taylor Rule. However, a standard Taylor Rule, designed to minimize the Central Bank Loss Function (CBLF), achieves a balanced outcome with minimal welfare losses and negligible emissions increases, aligning with central banks' traditional mandates while indirectly supporting environmental goals.

Unconventional monetary policies, particularly Green Quantitative Easing (QE), outperform Neu-

tral QE by redirecting financial resources toward sustainable investments. Green QE delivers greater welfare gains and more substantial emissions reductions compared to Neutral QE, especially in scenarios without abatement technologies. The optimal QE strategy, balancing welfare and CBLF, involves a moderate increase in central bank asset holdings with a strong green bias, yielding both economic stability and environmental benefits. Temporary QE programs mitigate short-term instability, while permanent interventions have a more significant impact on emissions reductions.

A key insight is that monetary policy should complement, rather than replace, fiscal climate policies. Emissions reductions emerge as a secondary effect of monetary interventions, primarily through their influence on financial conditions and capital reallocation. The distinction between welfare and CBLF objectives emphasizes that central banks cannot fully optimize both simultaneously, highlighting the importance of monetary-fiscal coordination to manage transition risks effectively. The findings challenge the notion that central banks must sacrifice stability for environmental goals, demonstrating that well-calibrated policies can support both within existing mandates.

From a policy perspective, central banks can improve economic resilience during the green transition by integrating emissions considerations into Taylor's rules or adopting green QE, particularly during periods of transition-induced instability. In normal times, they should focus on standard stabilization objectives, leaving primary climate responsibilities to fiscal authorities.

This study acknowledges a limitation in its deterministic simulation of transition risks, which may not fully capture the uncertainties of real-world low-carbon transitions. While the approach yields valuable insights, modeling uncertainty requires advanced global solution techniques to reflect systemic changes accurately. Despite this, the methodology effectively captures key variable behaviors in the simulated context.

Future research should address these limitations by exploring physical climate risks, macroprudential policy synergies, and sectoral or regional emissions variations to enhance policy recommendations. The interplay of monetary policy, financial stability, and climate goals remains a vital area for ongoing policy and academic exploration as the global economy transitions to sustainability.

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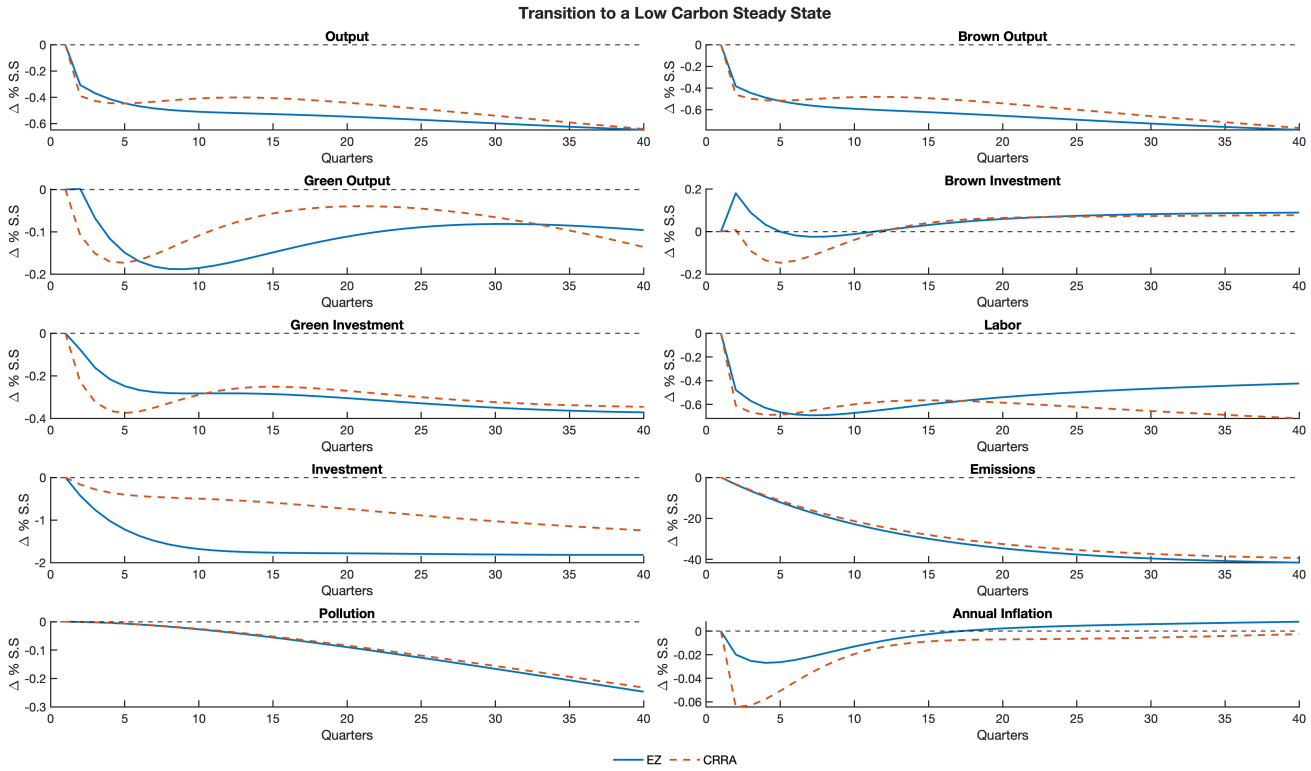
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Appendix A: Role of Preferences

The transition paths under Epstein-Zin (EZ) and CRRA preferences exhibit key differences that stem from the fundamental properties of each utility function. Epstein-Zin preferences allow for a separation between risk aversion and intertemporal elasticity of substitution (IES), while the standard CRRA utility ties these two parameters together. This distinction influences the economy's response to the transition to a low-carbon steady state.

Figure 9: Transition to a Low Carbon Economy -Epstein Zin vs CRRA - Real Variables



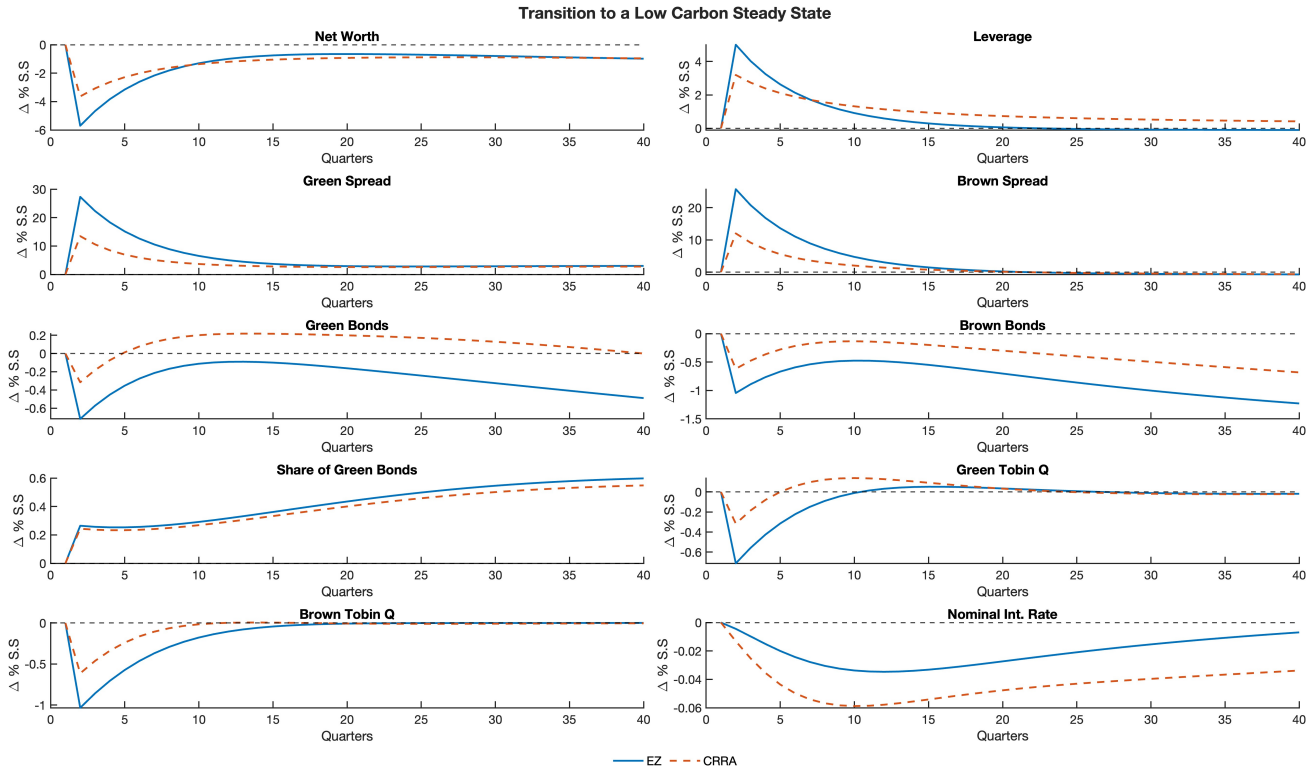
In the output and investment dynamics, the economy under EZ preferences exhibits a smoother adjustment compared to CRRA, particularly in green investment and green output. This is because agents with higher IES under Epstein-Zin preferences anticipate future gains from the transition and adjust their consumption and investment decisions accordingly. Under CRRA preferences, the adjustment path is more abrupt, as agents' risk aversion and elasticity of substitution are linked, leading to a stronger initial contraction in response to the carbon tax.

Labor and emissions follow distinct trajectories as well. The labor response under Epstein-Zin preferences is less volatile, as agents are more forward-looking and willing to smooth consumption over time, whereas CRRA agents exhibit sharper fluctuations. Similarly, emissions decline more grad-

ually under EZ preferences, suggesting that firms and households internalize the long-run benefits of green investment more effectively when IES is decoupled from risk aversion.

Financial variables further stress the role of preference structures. Green bond spreads and the share of green bonds increase more steadily under EZ preferences, indicating a stronger reallocation of capital towards green assets. Meanwhile, brown bond spreads remain higher for a longer period under CRRA, reflecting a more sluggish transition in financial markets. The smoother adjustment in net worth and leverage under Epstein-Zin preferences suggests that financial frictions play a smaller role in exacerbating volatility compared to the CRRA case.

Figure 10: Transition to a Low Carbon Economy -Epstein Zin vs CRRA - Financial Variables



Even if CRRA preferences highlight short-term economic distress, Epstein-Zin preferences are still preferable due to:

- Transition risks are inherently long-term , where EZ preferences allow for forward-looking behavior
- Financial markets matter, with EZ preferences allowing to capture the pricing of risk and investment shifts
- Macroeconomic stability is important, where CRRA could exaggerate short-term volatility, while

EZ provides smoother adjustment paths.

Appendix B: Calibrated Parameters

We follow Ferrari and Nispi Landi (2024) and calibrate ex-ante the parameters:

- $Lev = 6$
- $\frac{\bar{r}}{\bar{pi}} = R = 1.05$
- $RoW = \frac{e^{row}}{e} = 15.3$
- $\frac{k^G}{k} = 0.2$
- $\frac{g}{y} = 0.215$
- $\frac{b^P}{4y} = 0.0254$

And we find the ex post paratemers: $\left\{\theta, \iota, e^{row}, \zeta, g\right\}$

By using the net-worth evolution, we can find ι:

$$\iota = \frac{1 - \chi((r^G - R)lev + R}{lev}$$

Then, from the FOC of bankers, we can get the bank's discount factor:

$$\nu = \frac{1 - \chi}{1 - \chi\beta((r^G - R)lev + R)}$$

And from the leverage equation, we get the fraction of capital that can be diverted:

$$\theta = \frac{\nu}{lev} + \beta((r^G - R)\nu)$$

In the model, pollution is represented in arbitrary units. However, in order to align with real-world measurements, our aim is to calibrate the model so that the steady-state level of pollution corresponds to x^{GtC} (gigatons of carbon). This choice of x^{GtC} will result in a damage parameter, denoted as $\bar{D}$, that matches the estimate provided by Gibson and Heutel (2023). By achieving this calibration, we ensure that the model's pollution levels are more meaningful and relevant in the context of actual carbon emissions and their associated impacts.

$$\overline{D} = \overline{D_0} + \overline{D_1} x^{GtC} + \overline{D_2} x^{GtC2}$$

Where $\overline{D_1}$ and $\overline{D_2}$ are proposed by Gibson and Heutel (2023). We need to find D_1 and D_2 in our model. We define the rest of the world emissions as: $e^{row} = RoW \times \bar{e}$, and from the pollution stock in steady-state ($\overline{x}$). Then we get:

$$D_1 = \overline{D_1}\frac{x^{Gtc}}{\overline{x}}$$

$$D_2 = \overline{D_2}\left(\frac{x^{Gtc}}{\overline{x}}\right)$$

To calibrate the parameter α_0 that creates utility losses from pollution stock, we follow Barrage (2020) to get consumption losses equivalent to the damage in the output:

$$1 - (D_0 + D_1\bar{x} + D_2\bar{x}^2) = \frac{1}{\alpha_0\bar{x}}$$

$$\alpha_0 = \frac{1}{\bar{x}(1 - (D_0 + D_1\bar{x} + D_2\bar{x}^2)}$$

Appendix C: Banker's Problem Maximization

We solve this problem using the solution Ferrari and Nispi Landi (2024) proposed for this specific setting.

Let $t, t+i$ be the stochastic factor applying in period t to earnings at $t+i$. Each banker exits the market with probability $(1-\chi)$ getting NW_{t+1} at the beginning of period $t+i$. With probability χ, a banker continues in this activity. Therefore the value of a bank is:

$$V_t^f = \max \; E_t\left[\sum_{i=0}(1-\chi)\chi^i\beta^{i+1}M_{t,t+1}NW_{t+1+i}\right]$$

Subject to:

$$\frac{NW_t}{NW_{t-1}} = (r_t^G - r_t^B)lev_{t-1}^g + (r_t^B - \frac{r_{t-1}}{\pi_t})lev_{t-1} + \frac{r_{t-1}}{\pi_t} - \frac{\kappa_F}{2}(\frac{lev_t^g}{l_{t-1}} - b^*)^2 \tag{28}$$

Recursively writing the expected terminal wealth:

$$\frac{V_t^f}{NW_t} = \max \; E_t\left[(1-\chi)\; M_{t,t+1}\frac{NW_{t+1}}{NW_t} + \chi\beta M_{t,t+1}\frac{V_{t+1}^f}{NW_{t+1}}\right]$$

And following Gertler and Karadi (2011), financial intermediaries face the collateral constraint:

$$V_t^f(NW_t) \geq \theta b_t^f$$

$$\frac{V_t^f(NW_t)}{NW_t} \geq \theta lev_t$$

As the standard solution in this literature, we guess the solution:

$$\frac{V_t^f}{NW_t} = a_{gt}lev_t^g + a_{bt}lev_t + a_{ct}(\frac{lev_t^g}{lev_t} - b^*)^2 + a_{dt}$$

Being a_{kt} with $k = a, g, c, d$ the coefficients to be determined.

Rewriting the bank problem as:

$$\max \left[a_{gt}lev_t^g + a_{bt}lev_t + a_{ct}(\frac{lev_t^g}{lev_t} - b^*)^2 + a_{dt}\right] + (1+\gamma_{Ft}) - \gamma_{Ft}\theta lev_t$$

With γ_{Ft} being the Lagrange multiplier. The FOC are:

$$\left[a_{gt} + \frac{2a_{ct}}{lev_t}(\frac{lev_t^g}{lev_t} - b^*)\right](1 + \gamma_{Ft}) = 0$$

$$\left[a_{bt} - \frac{2a_{ct}lev_t^g}{lev_t^2}(\frac{lev_t^g}{lev_t} - b^*)\right](1 + \gamma_{Ft}) = \gamma_{Ft}\theta$$

Then, from the first FOC, we get the following:

$$a_{gt} = -\frac{2a_{ct}}{lev_t}(\frac{lev_t^g}{lev_t} - b^*)$$

We get the formula for γ_{Ft} from the second condition. Then, using the guessed solution, we get:

$$\frac{V_t^f}{NW_t} = \max\ E_t\left[(1-\chi)\ M_{t,t+1}\frac{NW_{t+1}}{NW_t} + \chi\beta M_{t,t+1}\frac{V_{t+1}^f}{NW_{t+1}}\right]$$

$$\frac{V_t^f}{NW_t} = \max\ E_t\left[(M_{t,t+1}\frac{NW_{t+1}}{NW_t}[(1-\chi) + \chi\frac{V_{t+1}^f}{NW_{t+1}}]\right]$$

$$\frac{V_t^f}{NW_t} = \max\ E_t\left[(M_{t,t+1}\nu_{t+1}\frac{NW_{t+1}}{NW_t}\right]$$

Where ν_t is the effective bank's SDF with $\nu_t = 1 - \chi + \chi\left[a_{bt} - \frac{2a_{ct}lev_t^g}{lev_t^2}(\frac{lev_t^g}{lev_t} - b^*)^2\right]$
Given the Banks' constraint by the evolution of net worth, we can find the remaining coefficients:

$$a_{gt} = \mathbb{E}_t\left[M_{t,t+1}\nu_{t+1}(r_{t+1}^g - r_{t+1}^b)\right]$$

$$a_{bt} = \mathbb{E}_t\left[M_{t,t+1}\nu_{t+1}(r_{t+1}^b - \frac{r_t}{\pi_{t+1}})\right]$$

$$a_{ct} = \mathbb{E}_t\left[M_{t,t+1}\nu_{t+1}\frac{r_t}{\pi_{t+1}}\right]$$

$$a_{dt} = -\frac{\kappa_F}{2}\,\mathbb{E}_t\left[M_{t,t+1}\nu_{t+1}\right]$$

Using the first FOC, we get the following:

$$E_t M_{t,t+1}\, \nu_{t+1} \left(r_{g,t+1} - r_{b,t+1} - \left(\frac{lev_{g,t}}{lev_t} - b^* \right) \frac{\kappa_F}{lev_t} \right) = 0$$

Now, we can get the respective expression for the optimal leverage:

$$\theta lev_t = a_{gt} lev_t^g + a_{bt} lev_t + a_{ct} (\frac{lev_t^g}{lev_t} - b^*)^2 + a_{dt}$$

$$lev_t = \frac{M_{t,t+1}\, \nu_{t+1} \left(\frac{r_t}{\pi_{t+1}} + \left(r_{g,t+1} - r_{b,t+1} \right) lev_{g,t} - \frac{\kappa_F}{2} \left(\frac{lev_{g,t}}{lev_t} - b^* \right)^2 \right)}{\theta - M_{t,t+1}\, \nu_{t+1} \left(r_{b,t+1} - \frac{r_t}{\pi_{t+1}} \right)}$$

Finally, using the previous conditions, we get the resulting formula for ν_t:

$$\nu_t = 1 - \chi +, E_t M_{t,t+1}\, \nu_{t+1}\, \chi \left(\frac{r_t}{\pi_{t+1}} + \left(r_{g,t+1} - r_{b,t+1} \right) lev_{g,t} + lev_t \left(r_{b,t+1} - \frac{r_t}{\pi_{t+1}} \right) - \frac{\kappa_F}{2} \left(\frac{lev_{g,t}}{lev_t} - b^* \right)^2 \right)$$

Appendix D: Additional Figures

Taylor Rule

Figure 11: Transition to a Low Carbon Economy - Conventional MP - Real Variables

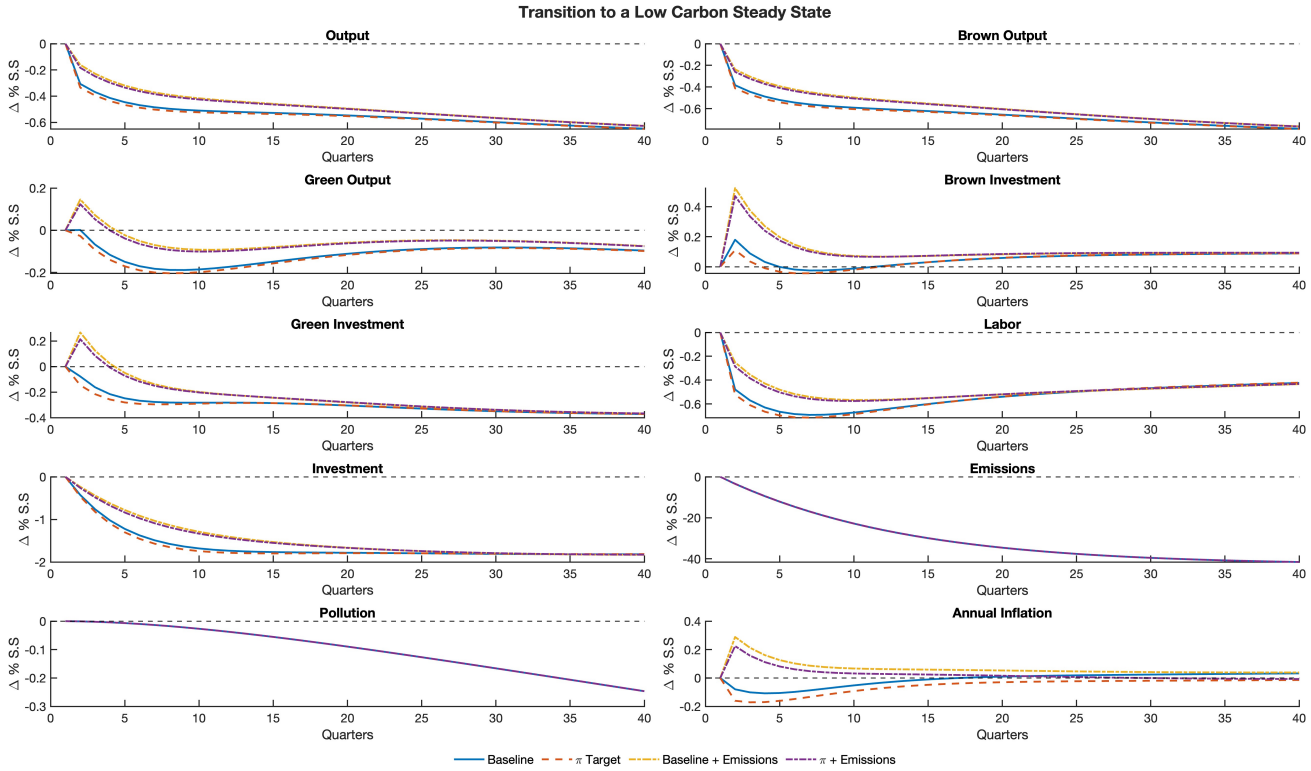
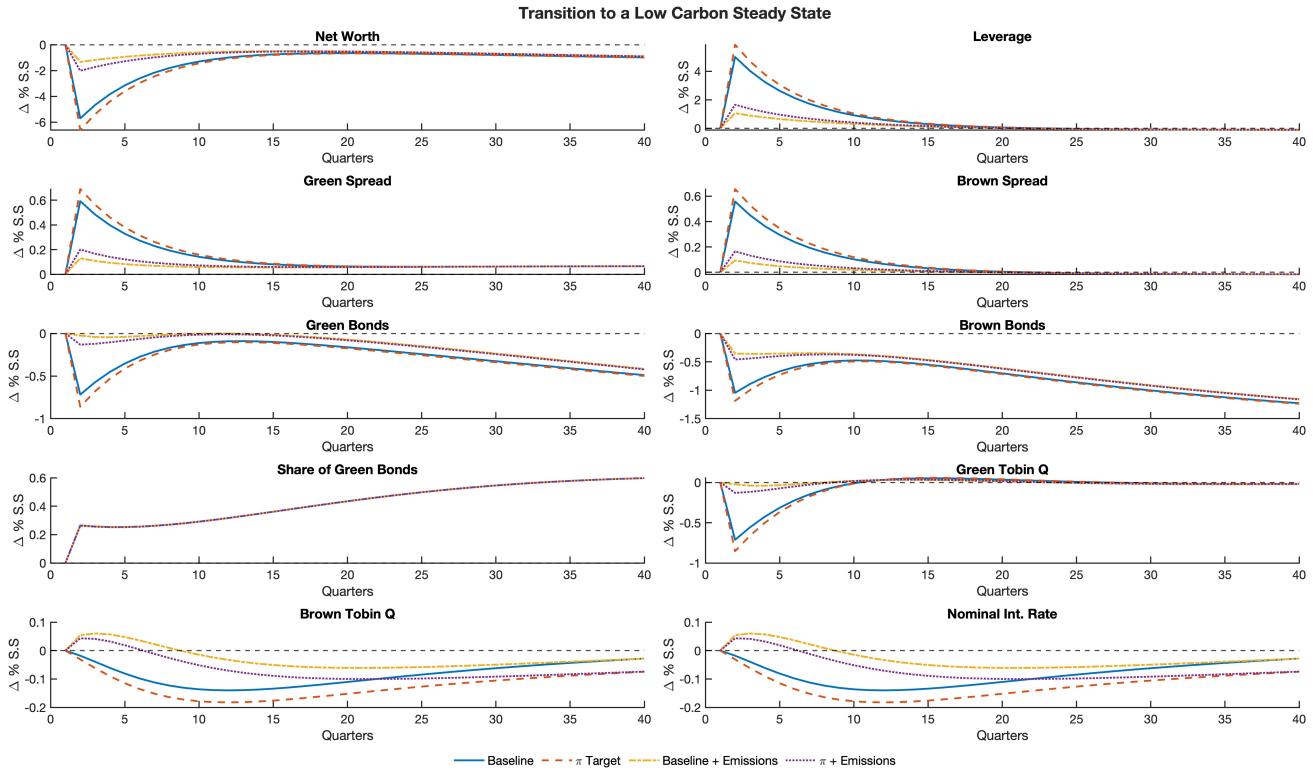


Figure 12: Transition to a Low Carbon Economy - Conventional MP - Financial Variables



Quantitative Easing

Figure 13: Transition to a Low Carbon Economy - Unconventional MP - Real Variables

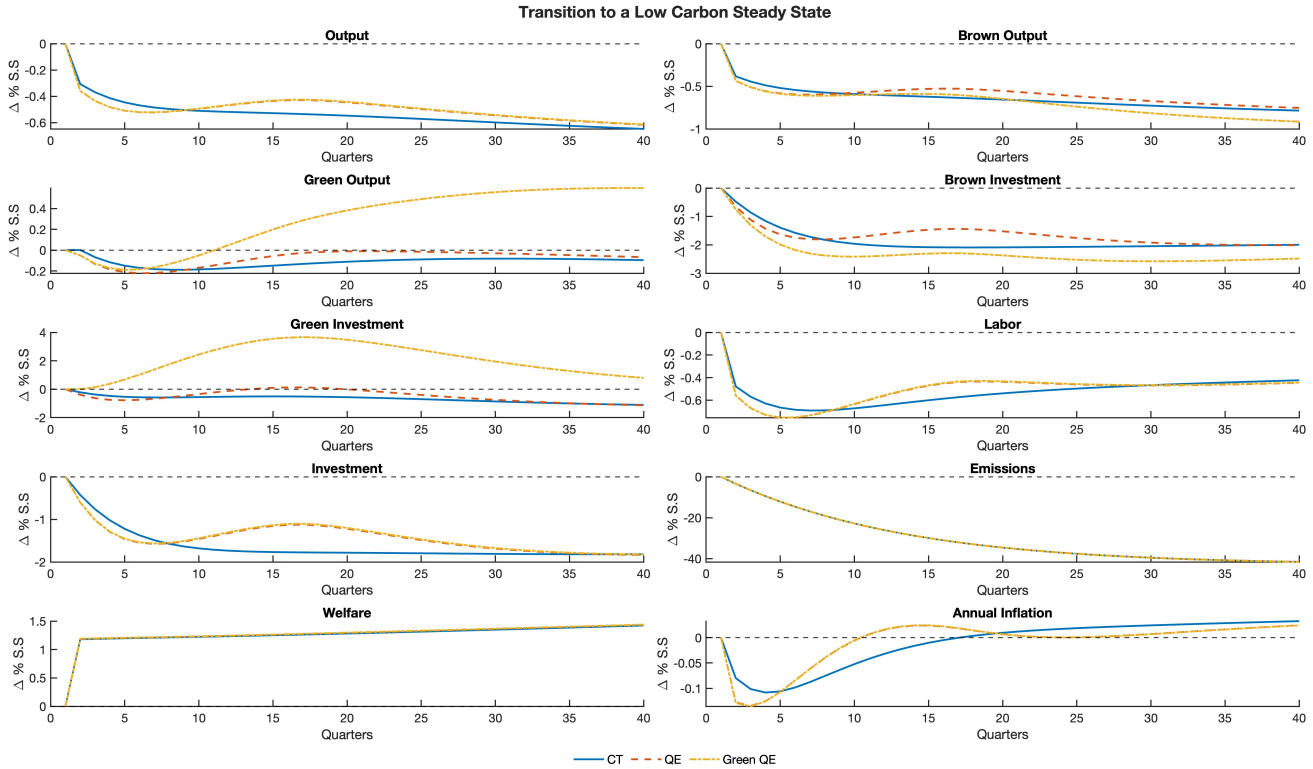
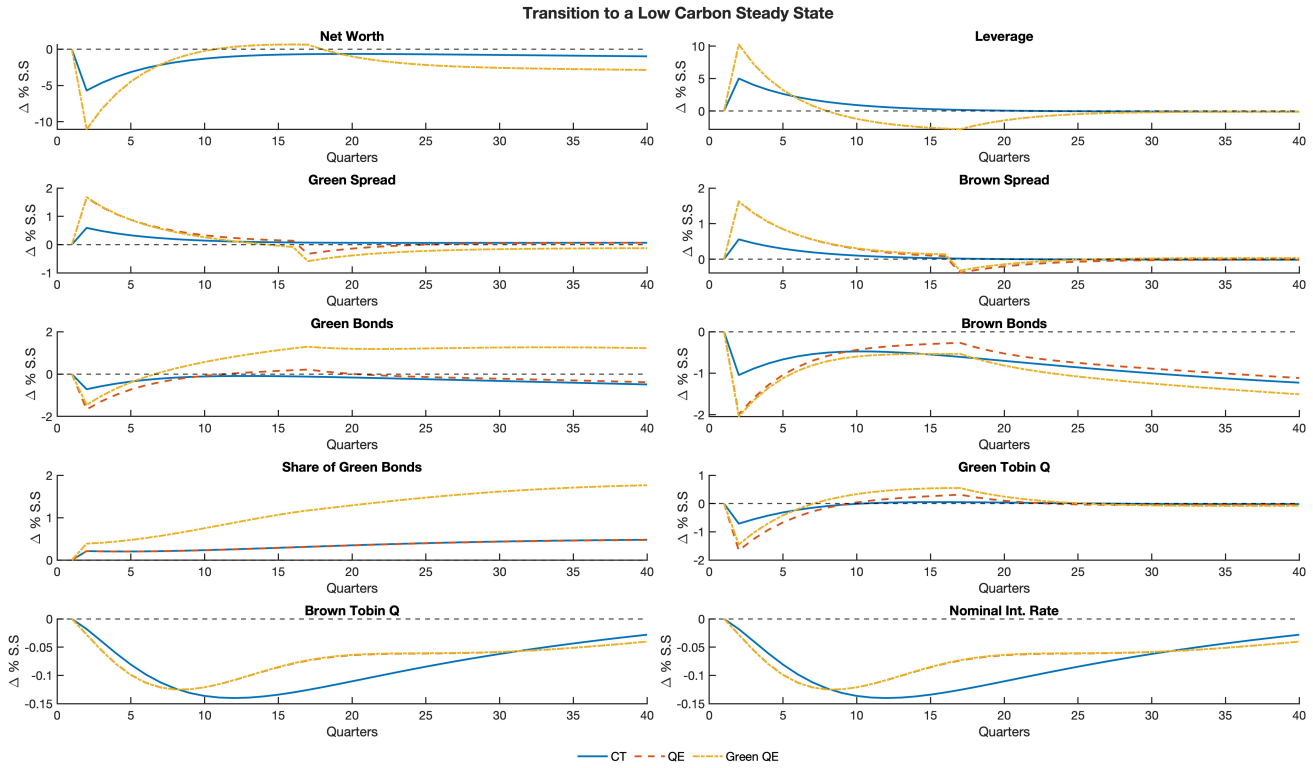


Figure 14: Transition to a Low Carbon Economy - Unconventional MP - Financial Variables



Appendix E: Transition to a Low Carbon Economy without Abatement Technology

Taylor Rule

Figure 15: Transition to a Low Carbon Economy - Conventional MP - Real Variables

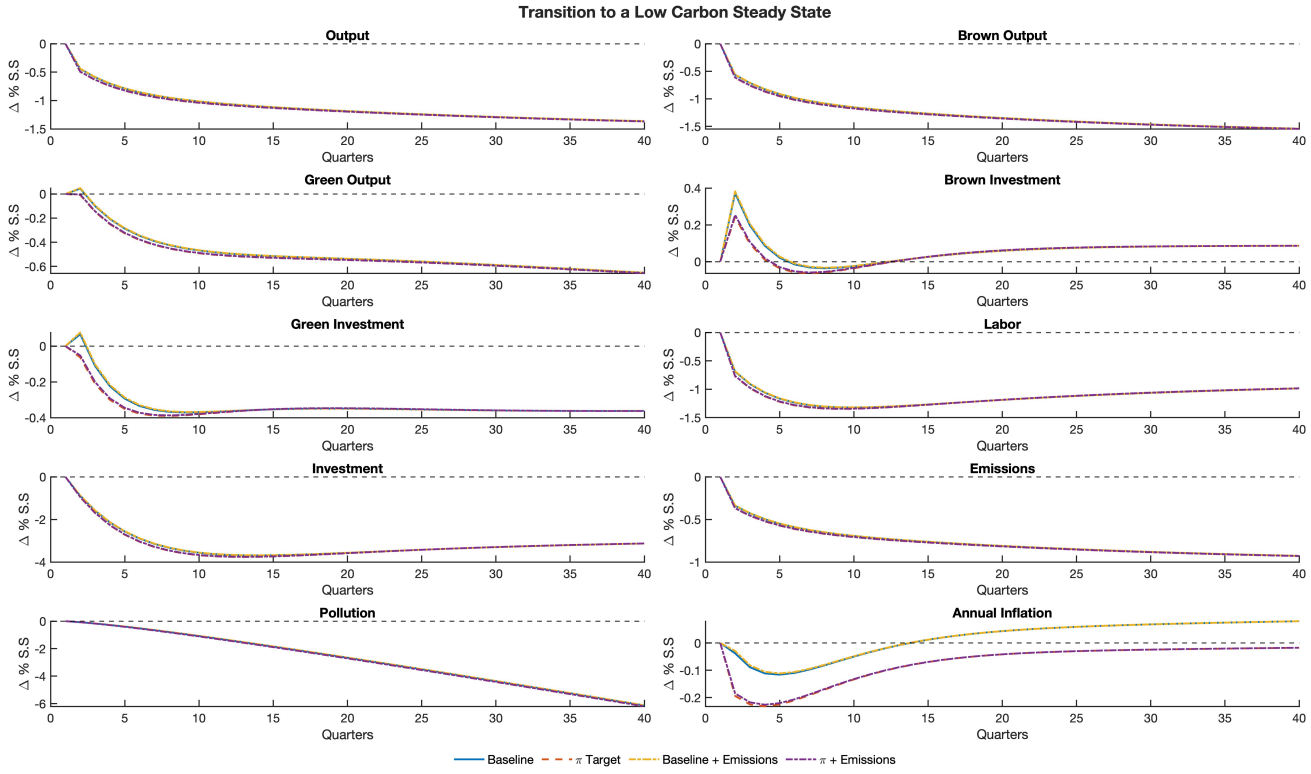


Figure 16: Transition to a Low Carbon Economy - Conventional MP - Financial Variables

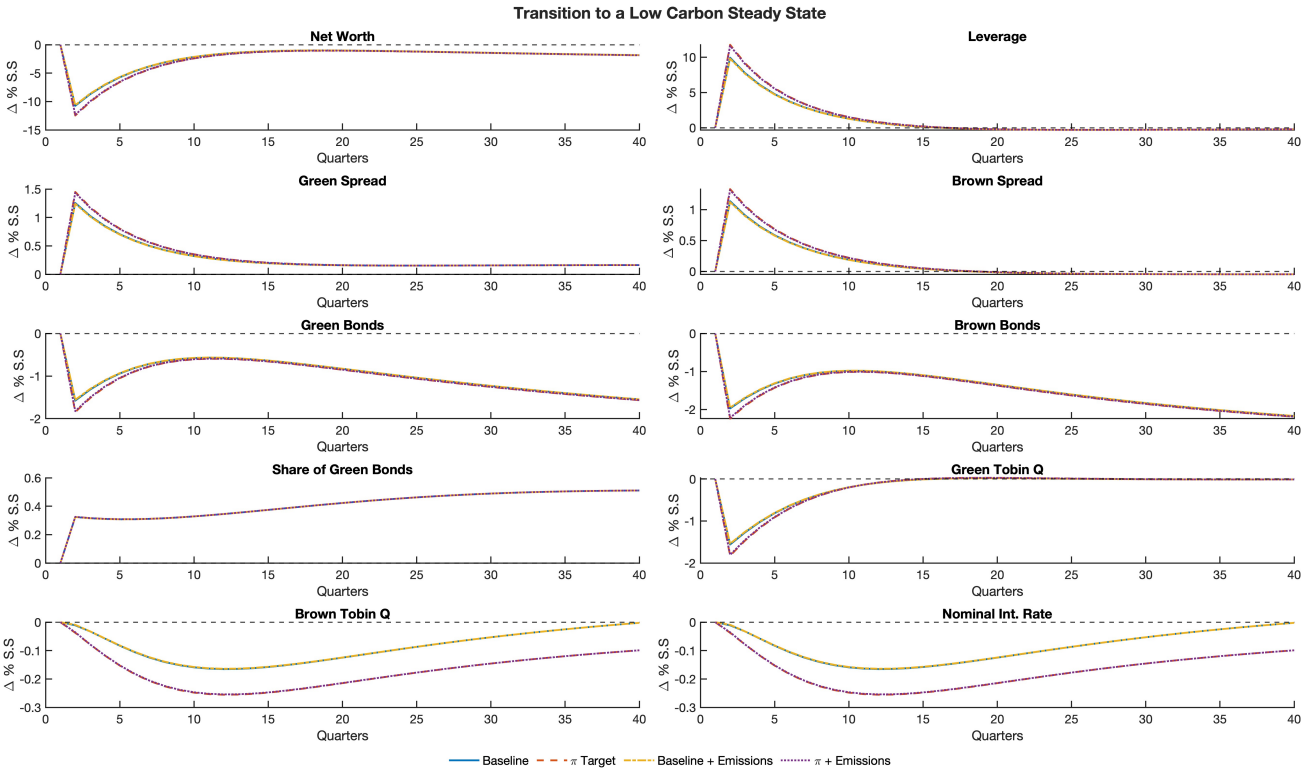


Table 9: Normative Analysis - Taylor Rule - Without Abatement Technology

Policy	Δ Welfare	Δ Output	Δ Emissions	Δ CB Loss Function
Baseline Taylor Rule	-	-	-	-
Inflation Target	-0.0006	-0.0091	-0.0053	-0.0541
Baseline + Emission Target	0.0043	-0.0001	0.0004	0.0001
Inflation + Emission Target	0.0058	-0.0092	-0.0049	-0.0540

Note: Δ Welfare,Output, Emissions CB Loss Function in % in relation to the baseline Taylor Rule

Quantitative Easing

Figure 17: Transition to a Low Carbon Economy - Unconventional MP - Real Variables

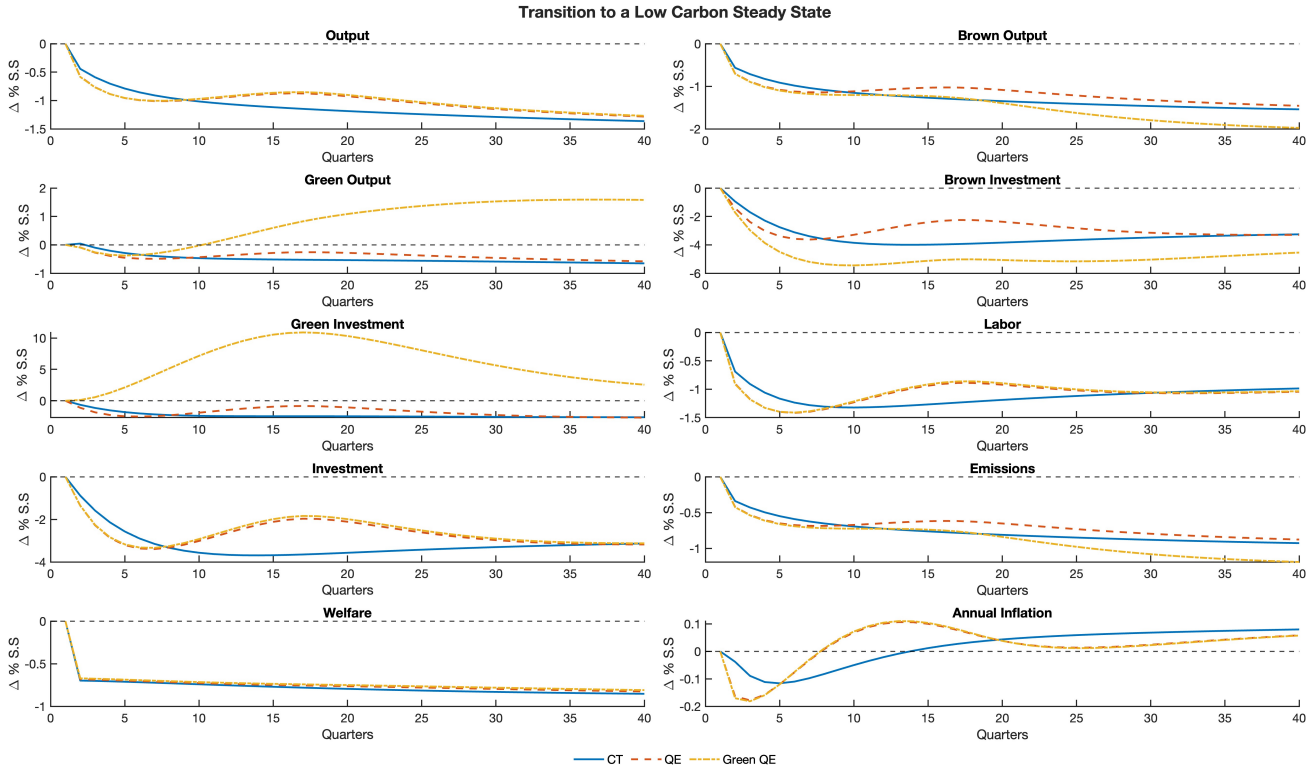


Figure 18: Transition to a Low Carbon Economy - Unconventional MP - Financial Variables

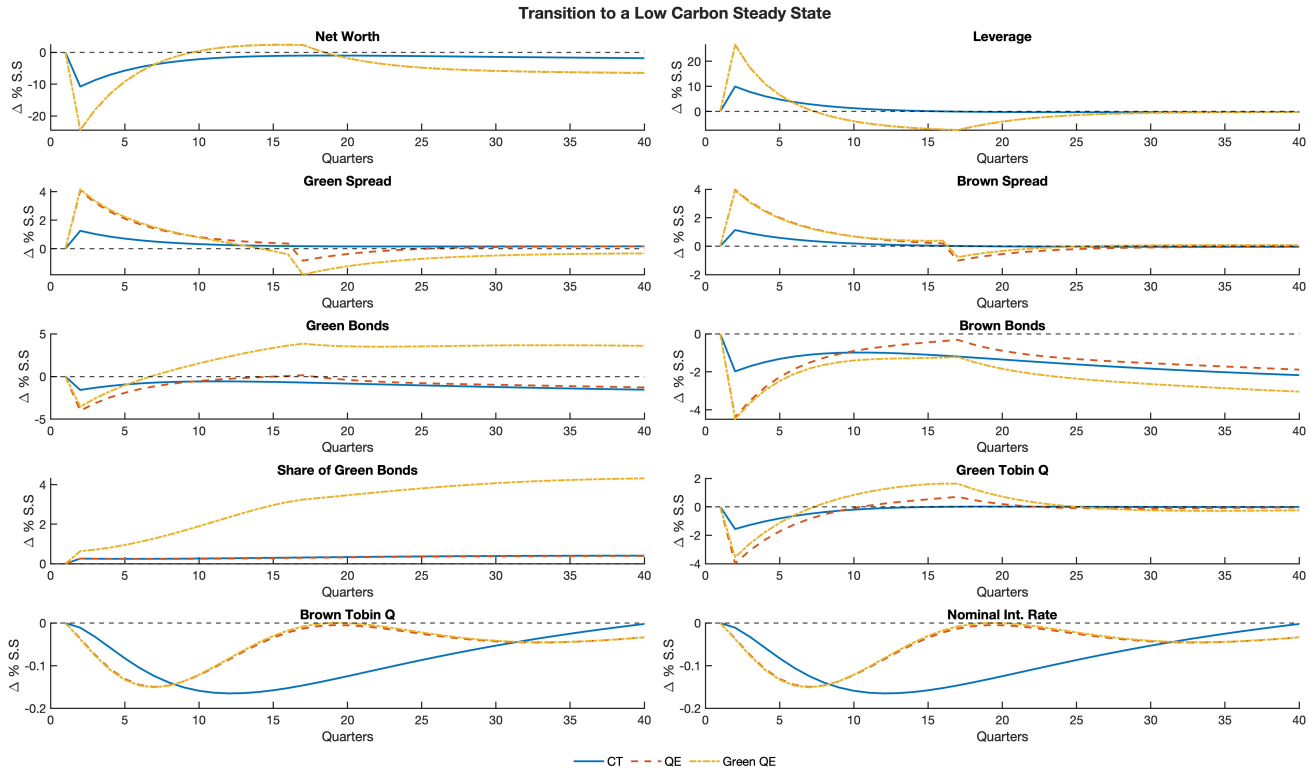


Table 10: Normative Analysis - Permanent Quantitative Easing - Without Abatement Technology

Policy	Δ Welfare	Δ Output	Δ Emissions	Δ CB Loss Function
Carbon Tax	-	-	-	-
Neutral QE	0.0167	0.0607	0.0376	-0.0028
Green QE	0.0329	0.0754	-0.2131	-0.0035

Note: Δ Welfare,Output, Emissions CB Loss Function in % in relation to the Carbon Tax scenario