# Climate Change and Carbon Policy: A Story of Optimal Green Macroprudential and Capital Flow Management

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## Abstract

What is the macro-financial impact of carbon policy, and how should reserve requirements be set to deal with climate-related transition risks? My empirical evidence shows a 0.7% output loss and a rise of 0.3% in inflation in response to the shock on carbon policy. Furthermore, I also observe financial instability and allocation effects between the clean and highly polluted energy sectors. To have a better prediction of medium and long-term impact, using a medium-large macro-financial DSGE model with environmental aspects, I show the recessionary effect of an ambitious carbon price implementation to achieve climate targets, a 40% reduction in GHG emissions causes a 0.7% output loss while reaching a zero-emission economy in 30 years causes a 2.7% lasting output loss over the medium to longer term. I document an amplified effect of the banking sector during the transition path. The paper also uncovers the beneficial role of pre-announcements of carbon policies in mitigating inflation volatility by 0.2% at its peak, and our results suggest well-communicated carbon policies from authorities and investing to expand the green sector. My findings also stress the use of optimal green monetary and financial policies in mitigating the effects of transition risk and assisting the transition to a zero-emission world. Utilizing a heterogeneous approach with macroprudential tools, I find that optimal macroprudential tools can mitigate the output loss by 0.1% and investment loss by 0.5%. Importantly, my work highlights the use of capital flow management in the green transition when a global cooperative solution is challenging.

***JEL Codes:*** Q58, E32, Q54, C11, E17, E52

***Keywords:*** Climate change, Environmental policy, Optimal policy, Transition risk

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# 1 Introduction

The issue of climate change has shifted from being a mere topic of discussion to an urgent problem that demands immediate global attention. The adoption of the Paris Agreement aims to limit the global temperature rise to below 1.5 to 2 degrees Celsius compared to pre-industrial levels. Since then, climate change has emerged as a significant concern on the global economic policy agenda. According to IMF (2022), greenhouse gas emissions must be reduced by 25% to 50% to attain the global warming mitigation objective. Both developed and emerging economies are committed to achieving a zero-emission economy by 2050, as stated in the International Energy Agency (IEA) report by Bouckaert et al., 2021. To achieve the Paris Agreement target, it is necessary to significantly increase the carbon price. However, such intervention may have macroeconomic implications and pose macroeconomic risks, referred to as "transition risks." Hence, it is natural to ask how large the impact of carbon prices on the economy is, and more importantly, what can potentially be done to mitigate the risk.

This paper studies the effects of carbon policy and potential policies to mitigate transition risk on the macroeconomic environment. To achieve this, I employ a combination of empirical analysis and theoretical modelling. Firstly, I conduct empirical analysis using Bayesian Local Projection techniques to examine the impact of carbon policy in the Euro Area (EA) from 2005 to the end of 2019. Secondly, I utilize an enriched large NK-DSGE model to study the effect of carbon prices to achieve specific climate targets. This analysis allows us to assess the implications of different carbon price levels and explore potential policies that policymakers can adopt to mitigate these effects and facilitate the transition to a greener economy.

With our empirical evidence, I uncover the recessionary effect of the carbon price using the same approach as Känzig (2023). Recent work by Känzig (2023) using high-frequency data shows that the carbon price has a contractionary effect on output growth and inflation. This paper extends the analysis by focusing on macroeconomic aggregates, financial variables, as well as the performance of high and low-emission sectors. Our findings indicate that a carbon policy shock can reduce emissions but at the cost of economic growth and inflation.

Furthermore, it leads to an increase in credit spreads and the financial stress index, suggesting potential financial instability resulting from the carbon policy shock. These results contradict the findings of Metcalf (2019), which use panel data from European countries with annual data and show non-significant effects of the carbon price on economic growth, employment, and inflation. Similar non-significant effects are documented by Metcalf and Stock (2020*a*) and Konradt and di Mauro (2023) using yearly data. Additionally, I confirm the allocation effect of the carbon price between the green and brown sectors, but we do not observe a contractionary effect on the energy sector stock price index.

Moving forward, using the theoretical model, I address three important questions:

1) What does the transition path look like in different scenarios of carbon price implementation?

2) Can a joint set of monetary, credit, and macroprudential policies assist the transition path?

3) What should be done with foreign capital to promote the green transition in our domestic economy?

To do that, I extend a standard New Keynesian Dynamic Stochastic General Equilibrium (NK-DSGE) model to incorporate environmental concerns. Specifically, I introduce an environmental externality represented by greenhouse gas (GHG) emissions, along with a carbon price (tax) and abatement cost. Additionally, I incorporate further features into the model, such as default risk and working capital constraints faced by both the green and brown sectors due to external borrowing. Lastly, I introduce a banking sector subject to macroprudential tools, such as reserve requirements for loans.

To study the effect of our ambitious climate policy, I focus on two scenarios. In the first case, the carbon price is implemented to achieve a 40% reduction in current emission levels. In the second case, the carbon price increases linearly with communication from the government until we achieve a zero-emission economy after 30 years. In this context, I document our model predictions through three main cases: an unanticipated carbon price hike, a ”forward guidance” carbon policy, and the transition path toward a zero-emission economy.

Our findings indicate that financial frictions amplify the recessionary effects of an ambitious carbon policy. Given the dominant amount of carbon-intensive assets within the financial sector, an ambitious carbon price hike might trigger financial instability. We confirm the role of financial frictions in the sense of costly state verification loans similar to Bernanke et al. (1999) in amplifying the effect of transition risk. Hence, credit policy toward the green sector can be the most promising tool in mitigating the transition risk by allocating resources to the low-carbon sector and accelerating the transition to a zero-emission economy. Furthermore, our analysis suggests that policymakers should effectively communicate climate policies to reduce fluctuations in transition risk within the economy.

An essential aspect of our modelling framework involves the utilization of green macroprudential policy. These measures are designed to alleviate financial constraints faced by the green sector, enabling the allocation of additional capital to green firms. The objective is to enhance the financial condition of the green sector, which is less directly affected by the ambitious introduction of a carbon price. By doing so, these measures aim to mitigate the recessionary impact of a significant carbon price hike.

In the optimal policy analysis, the results suggest that policy tools with allocation effects have the potential to reduce the severity of transition risk, while monetary policy alone seems to be ineffective in addressing this issue. Although the green sector is unable to fully replace the brown sector in the short and medium term, the policy set that includes a reduction in reserve requirements for green loans and a green capital inflow subsidy shows promising effects. The findings indicate that green credit policy alone may not significantly reduce pollution, but when combined with an ambitious carbon price, it can help mitigate the severity of the transition by directing more credit towards the green sectors. Furthermore, the implementation of green capital controls can further mitigate the impact by channelling foreign capital into green sectors, albeit at the cost of welfare due to distortions in domestic deposits. Overall, both macroprudential tools on domestic and foreign capital generate welfare gains.

This study provides valuable insights into the effects of carbon policy and the potential effectiveness of various mitigation strategies in managing transition risk. By understanding these dynamics, policymakers can make informed decisions to strike a balance between environmental sustainability, macroeconomics, and financial stability.

**Related Literature:** This work belongs to three strands of literature that study the empirical evidence of transition risk in the macroeconomic environment, environmental macroeconomic modelling, and macroprudential policy.

First, my work relates to a fast-growing literature on the effect of carbon prices on the macroeconomic environment. As the literature grows quickly, I only provide a part of it with a focus on the macroeconomic environment. Using yearly data, Metcalf (2019), Metcalf and Stock (2020*a*), and Metcalf and Stock (2020*b*) conduct the analysis using annual panel data on 15 European countries and British Columbia from 1990. They find no significant impact of carbon pricing on GDP or the unemployment rate. Konradt and di Mauro (2023) conducts a quite similar analysis with a focus on inflation using the EU Emissions Trading System (ETS), which has only been established since 2005. However, they also find a non-significant impact on inflation. In the empirical part, my paper uses the method proposed by Känzig (2023), where he uses the carbon policy surprise series in Europe as an instrument to estimate the carbon policy shock. Using monthly data, his work finds a significant effect of carbon policy on the macroeconomic environment. On firm-level data, Berthold et al. (2023) use the same carbon policy measurement from Känzig (2023) with European countries and find that the effect of carbon policy is more severe for firms with higher carbon emissions. Using the same approach, Hengge et al. (2023) focus on the stock return of more than 2,000 publicly listed European firms. They find that the carbon policy can increase the cost of capital for emission-intensive firms even when they do not participate in the ETS. Our paper mainly focuses on quarterly macro-financial data in the Euro Area as well as measurements for the high and low-emission industries.

The second strand of related literature is on the development of environmental economic models, the inclusion of environmental aspects into equilibrium models originated in the Integrated Assessment Models (IAMs). Nordhaus (1977) provides a pioneering work with Dynamic Integrated Models of Climate Change and the Economy (DICE). Some other pioneering works on Environmental Real Business Cycle (E-RBC) models include Fischer and Springborn (2011) and Heutel (2012). Annicchiarico and Di Dio (2015) provide the New-Keynesian (NK) model with environmental aspects, which gives rise to monetary policy analysis. In Dück and Le (2023), they document the effect of transition risk in many scenarios and find a significant output loss and green inflation in response to an ambitious carbon price policy. Some notable works on macroprudential and green quantitative easing are Benmir and Roman (2020), Carattini et al. (2021), Ferrari and Landi (2021), Abiry et al. (2022), Ferrari and Nispi Landi (2023) and many others. Those papers analyze with environmental two-sector models, brown and green sectors. This setup aims to study policies with allocation effects between green and brown sectors to mitigate the effect of transition risk. However, those papers do not include the default risk of the production sector where the effect of carbon price originates. Coenen et al. (2023) use the ECB's New Area-Wide Model (NAWM) with disaggregated energy production to study different scenarios of carbon policy. Our paper is closer to Giovanardi et al. (2023), which also includes working capital for the study of climate policy. Nevertheless, Giovanardi et al. (2023) do not include the carbon price in their model.

Lastly, my work also relates to the vast literature on macroprudential policy. After the Global Financial Crisis, more attention has been paid to the usage of macroprudential policy. Many seminal works after the GFC include Angeloni and Faia (2009), Sgherri and Gruss (2009), Covas et al. (2010), Angelini et al. (2014). Angeloni and Faia (2009) is among the first to investigate the interaction of monetary policy and Basel-like capital ratios. Angelini et al. (2014) find that countercyclical capital requirements policy can usefully interact with monetary policy when financial shocks destroy bank capital. Quinta and Rabanalb (2014) uses a two-country economy to find that the introduction of a macroprudential rule would help in reducing macroeconomic volatility, and improve welfare. Leduc and Natal (2017) provides a tractable framework for reserve requirement policy. Lastly, a recent work by Chang et al. (2019) studies the allocation effect of reserve requirements in China. This work relates vastly to the work of Leduc and Natal (2017) and Chang et al. (2019) when I propose the heterogeneous approach of macroprudential tools to deal with transition risk.

The rest of the paper is organized as follows. In section 2, I document the empirical evidence of carbon policy. In section 3, I present our model, outlining its key components and specifications. In section 4, I delve into the analysis of the different climate policy scenarios. Then, I conduct optimal policy in section 5 and section 6. Section 7 provides concluding remarks summarizing the main findings.

# 2 Empirical Evidence

In this section, I provide some empirical evidence of carbon policy on macroeconomic aggregates. I take advantage of carbon policy shock from the novel work of Känzig (2023). Similar to Känzig (2023), the paper uses high-frequency data on carbon policy announcements to identify the carbon policy shock following Stock and Watson (2018) method. As mentioned earlier, some empirical work using yearly data finds non-significant effects of the carbon price on the macroeconomic aggregate. Using the method of Känzig (2023), I provide some empirical motivation on the effect of the carbon price using the Euro Area quarterly data and the novel method of Bayesian Local Projection (BLP). BLP can maintain the flexibility of LPs while also preserving a level of estimation uncertainty similar to that of Bayesian VARs with conventional macroeconomic priors[1]. First, I confirm the results of Känzig (2023) on the recessionary effect of carbon pricing on GDP, consumption and investment. Second, I provide the impulse response for monetary and financial variables as well as green and brown sector measurements. Lastly, we also observe the effect of carbon policy on international aspects such as capital account and exchange rate.

All data are expressed in real terms and entered our estimation in log form except inflation rate, Euribor rate, unemployment rate, and credit spread. Our data are taken from the ECB data warehouse and Eurostat in the period from 2005 to the end of 2019. The description of the data can be found in the Appendix.

## 2.1 Carbon Policy Shock Identification

In this part, I describe how to identify the shock to feed into the BLP later. As the method to extract the shock is identical to Känzig (2023), I will use their notation for convenience. For further reading on derivation, Stock and Watson (2018) provide a detailed derivation of the method. Consider the standard VAR model:

$$\mathbf{y}_t = \mathbf{b} + \mathbf{B}_1 \mathbf{y}_{t-1} + \cdots + \mathbf{B}_p \mathbf{y}_{t-p} + \mathbf{u}_t \tag{1}$$

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[1] Känzig (2023) use standard Local Projection for an exercise on quarterly data.

In this context, $p$ represents the lag order. $\mathbf{y}_t$ is an $n \times 1$ vector comprising endogenous variables, while $\mathbf{u}_t$ is a $n \times 1$ vector denoting reduced-form innovations with a covariance matrix of $\text{Var}\left(\mathbf{u}_t\right) = \boldsymbol{\Sigma}$. $\mathbf{b}$ is an $n \times 1$ vector representing constants, and $\mathbf{B}_1, \ldots, \mathbf{B}_p$ are $n \times n$ coefficient matrices.

Assuming the VAR is invertible, we express the innovations $\mathbf{u}_t$ as linear combinations of structural shocks $\varepsilon_t$:

$$\mathbf{u}_t = \mathbf{S}_t \varepsilon_t \tag{2}$$

The structural shocks $\varepsilon_t$ are defined to be mutually uncorrelated as $\text{Var}\left(\varepsilon_t\right) = \boldsymbol{\Omega}$ is diagonal. From the invertibility assumption (2), we derive the standard covariance restrictions $\Sigma = \mathbf{S}\Omega\mathbf{S}'$. Our goal is to characterize the causal impact of a single shock, denoted as the carbon policy shock, $\varepsilon_{1,t}$. Hence, we seek to identify the structural impact vector $\mathbf{s}_1$, corresponding to the first column of $S$. External instruments are employed for identification, assuming the presence of an external instrument $z_t$ (in this case, the carbon policy shock series). The validity condition for $z_t$ as an instrument is:

$$E\left[z_t \varepsilon_{1,t}\right] = \alpha \neq 0 \tag{3}$$

$$E\left[z_t \varepsilon_{2:n,t}\right] = \mathbf{0} \tag{4}$$

where $\varepsilon_{1,t}$ is the carbon policy shock and $\varepsilon_{2:n,t}$ is an $(n-1) \times 1$ vector of the other structural shocks. Assumption (3) represents the relevance requirement and assumption (4) signifies the exogeneity condition. These assumptions, combined with the invertibility requirement (2), identify $s_1$ up to sign and scale:

$$\mathbf{s}_1 \propto \frac{E\left[z_t \mathbf{u}_t\right]}{E\left[z_t \mathbf{u}_{1,t}\right]} \tag{5}$$

provided that $E\left[z_t \mathrm{u}_{1,t}\right] \neq 0$. To enhance interpretation, we scale the structural impact vector such that a positive unit value of $\varepsilon_{1,t}$ has a unit positive effect on $y_{1,t}$, i.e., $s_{1,1} = 1$. The estimation is implemented using a two-stage least square procedure. Taking $z_t$ to be the instrument, we estimate the coefficients by regressing $\hat{\mathbf{u}}_t$ on $\hat{\mathbf{u}}_{1,t}$.

From the monthly VAR, we pin down the as $CPShock_t = \mathbf{s}_1' \Sigma^{-1} \mathbf{u}_t$ similar to Stock and Watson (2018) and estimate the effects using Bayesian Local Projection[2] with quarterly data:

$$y_{i,t+h} = \beta^i_{h,0} + \psi^i_h CPShock_t + \beta^i_{h,1} y_{i,t-1} + \ldots + \beta^i_{h,p} y_{i,t-p} + \xi_{i,t,h} \tag{6}$$

There are several reasons that BLP is chosen for the main analysis. Bayesian techniques enable the resolution of the empirical dichotomy between VARs and LPs by effectively addressing the standard bias-variance trade-off, which lies at the core of the decision between direct and iterated methods as pointed out by Ferreira et al. (2023). They show that BLP are less subject to misspecification problems compared to VARs and result in smaller estimation uncertainty relative to standard Local Projection by Jordà (2005).

## 2.2 Macroeconomic Effects

In Figure 1, we observe the recessionary effect on macroeconomic aggregate under quarterly frequency. We see a decrease in real GDP by 0.6% as well as consumption and investment. In addition, the unemployment rate increases significantly. Using quarterly inflation data, I find a significant increase in inflation initially to 0.3% (annualized). The policy rate increases to cope with the on-impact rise of inflation. The results are similar to Känzig (2023) for monthly data. The potential explanation for the differences in our results compared to Konradt and di Mauro (2023) is the carbon policy shock might include the surprise effect of carbon pricing that might not be observed in yearly data.

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[2] For detailed derivation in Bayesian Local Projection, viewers can go to Ferreira et al. (2023).

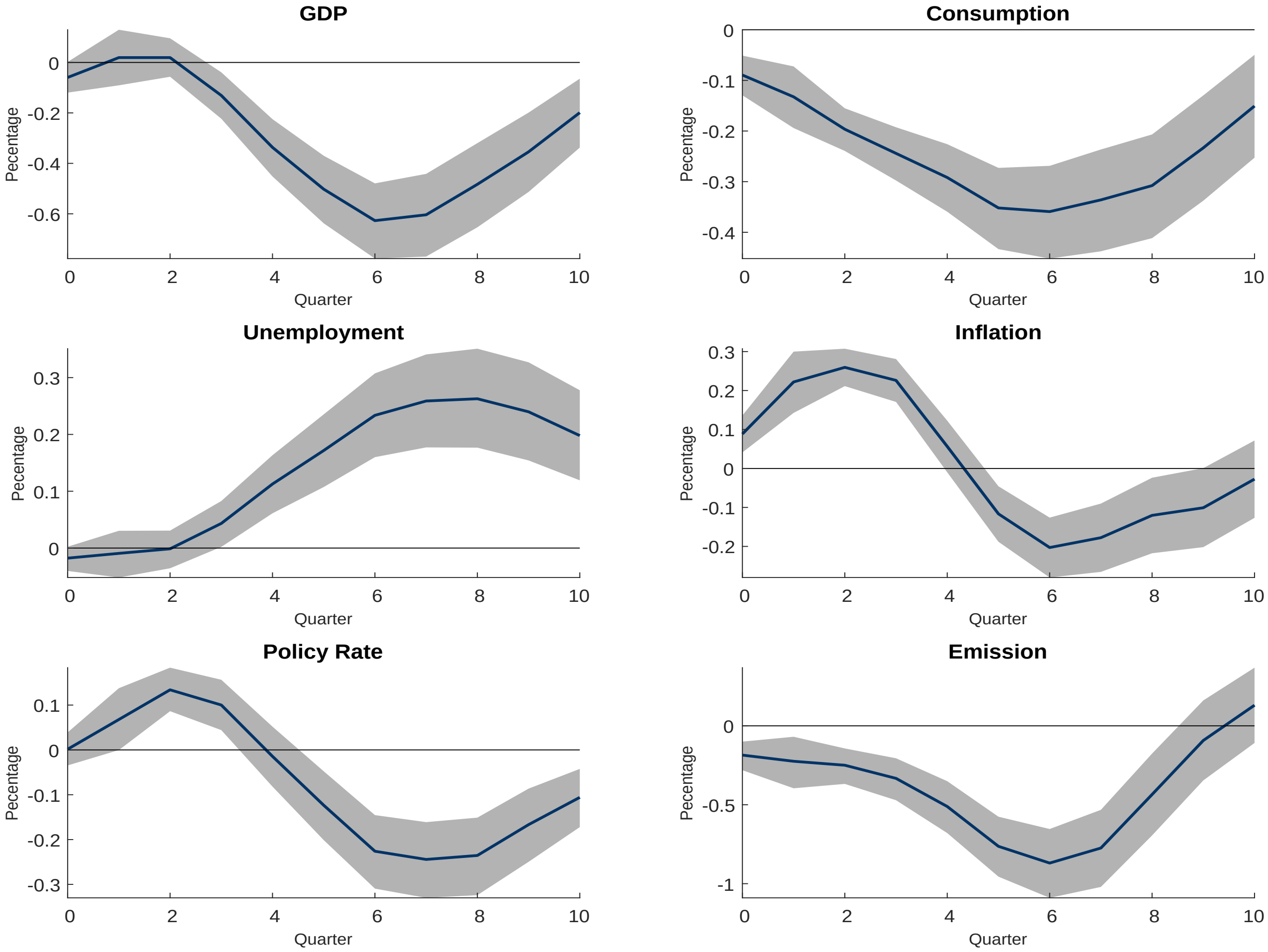

**Figure 1:** The impulse response of a 1 standard deviation carbon policy shock using BLP. The grey shade shows a 68% credible set of our estimation.

## 2.3 Macro-Financial Effects

In our extended analysis, I incorporate additional financial data. Figure 2 illustrates that the increase in carbon price leads to a credit spread widening of approximately 1%. Furthermore, the stock price, as measured by the STOXX600 index, experiences a significant decrease of around 5%. I also include the measurement of financial stress by Monin (2019), which indicates an increase in financial stress. These findings raise concerns about the potential impact of surprise carbon policy on financial stability, which could pose challenges for policymakers.

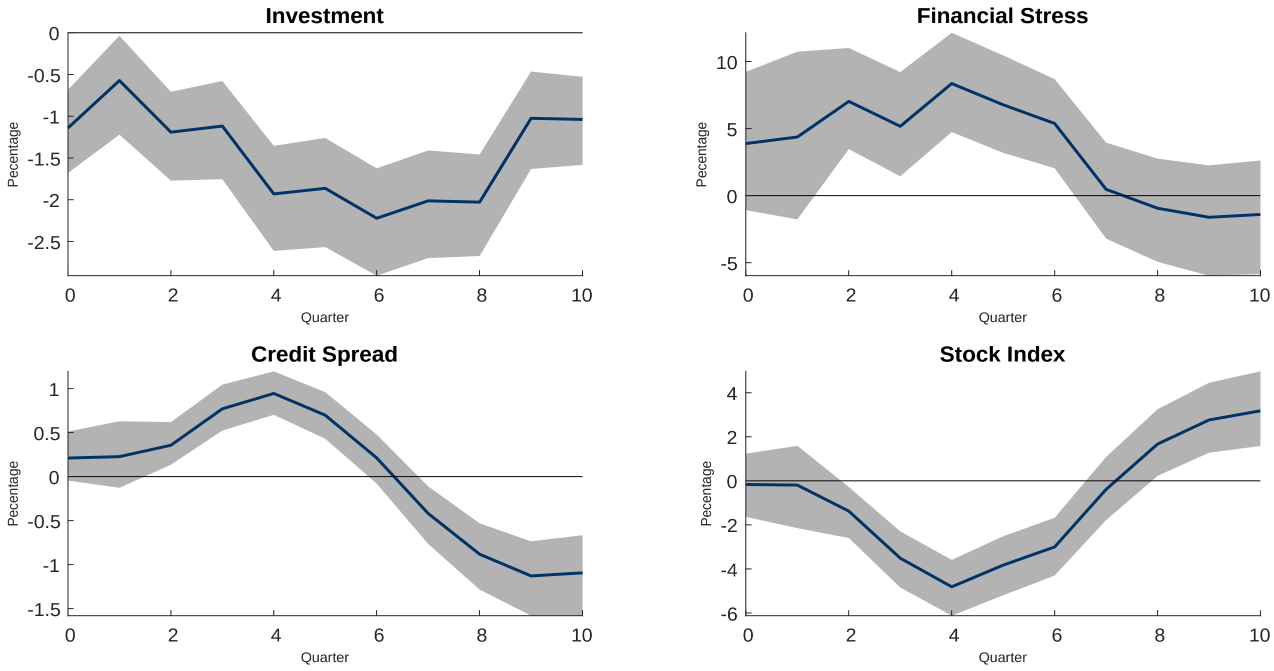

**Figure 2:** The impulse response of a 1 standard deviation carbon policy shock using BLP. The grey shade shows a 68% credible set of our estimation.

Additionally, I consider the impact of carbon prices on the international aspect of the Euro Area. Given that Euro Area trade constitutes approximately half of its GDP, I analyze the effects of carbon shock on the current account and exchange rate. In Figure 23, I observe that the carbon policy shock results in an appreciation of the Euro. This effect is driven by the initial increase in the policy rate, which persists over time. Moreover, we note a decline in the ratio of current accounts to GDP, which decreases by more than 0.4% under our specification.

## 2.4 Green and Brown Performance

In this section, I incorporate data on the performance of the green and brown sectors to examine the allocation effect of carbon policy. One challenge we face is classifying firms into green and brown sectors. While the common approach is to use ESG scores, these scores are subject to updates over time, making it challenging to ensure consistency when using long-term stock price data. To address this, I adopt the market-based approach proposed by Jung et al. (2021) and use ETF data on the energy industry. Specifically, I utilize VanEck

Vectors Coal ETF (KOL) as a measure of brown sector performance and iShares Clean Energy ETF (ICLN) as a measure of green sector performance. Although these indexes use global data, I believe they provide a good approximation of the green and brown sectors, given the prominence of the EU carbon trading platform.

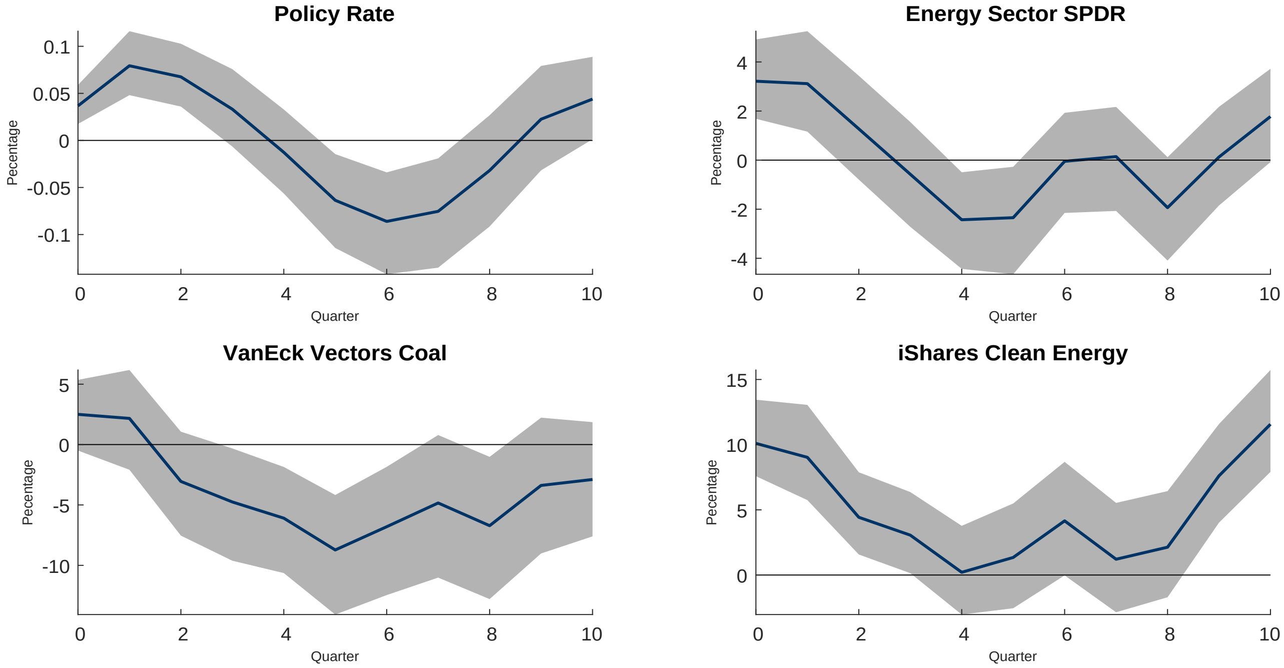

**Figure 3:** The impulse response of a 1 standard deviation carbon policy shock using BLP. The grey shade shows a 68% credible set of our estimation.

Figure 3 presents the results of our analysis, demonstrating the allocation effect of carbon policy. We observe a decrease in the price of highly polluted sectors, such as those relying on coal, and an increase in the asset prices of clean energy firms. Notably, we do not observe a decrease in the energy sector index (XLE), suggesting that carbon policy does not lead to a decline in the overall energy sector. However, this may be attributed to the higher price of energy resulting from the rise in carbon prices, which is consistent with the findings of Känzig (2023) using monthly data on HICP energy and oil prices.

In the Appendix, I provide additional results using Bayesian VAR with external instruments and standard Local Projection. Both methods yield similar results, confirming the robustness of our findings. Furthermore, the Appendix includes various robustness checks to further support the validity of our analysis such as using the shadow rate to account for zero lower bound and variation in lags.

In our empirical analysis, I find evidence that carbon pricing has negative effects on key macroeconomic aggregates and initially leads to an increase in inflation, commonly referred to as ”greenflation.” These findings are based on quarterly data and obtained using the Bayesian Local Projection (BLP) method. Additionally, our results indicate an increase in the green sector and a decrease in the brown sector, reflecting the impact of carbon policy on sectoral performance. Moreover, carbon policy implementation is shown to increase financial instability and financial stress, highlighting the crucial role of the financial sector in the context of carbon policy.

In the next section of the paper, I extend our analysis by incorporating a NK-DSGE model that captures heterogeneity in the production and financial sectors. This modelling framework allows us to examine the effects of carbon policy in a more comprehensive manner. Importantly, I propose the use of heterogeneous macroprudential policy as a means to mitigate the risks associated with carbon policy implementation.

# 3 Theoretical Model

The subsequent model features two kinds of intermediate firms, green and brown firms that have access to different credit channels with a presence of financial frictions and are subject to a macroprudential tool.

## 3.1 Households

Households maximise the following objective function:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[ log(C_t - \kappa C_{t-1}) - \Psi \frac{H_t^{1+\varphi}}{1+\varphi} \right] \tag{7}$$

subject to the budget constraint:

$$C_t + I_t + \frac{D_t^g + D_t^b}{P_t} = r_t^k K_{t-1} + w_t H_t + r_{t-1} \frac{D_{t-1}^g + D_{t-1}^b}{P_t} + T_t \tag{8}$$

where $C_t$ denotes total consumption, $D_t^g$ stands for deposits to green banks, and $D_t^b$ stands for deposits to brown banks[3], $I_t$ is the household's investment, $r_t^k$ stands for the real return on capital, $w_t$ denotes the real hourly wage and $H_t$ is total labour, $K_{t-1}$ stands for the physical capital at time t, $r_{t-1}$ is the risk-free nominal interest rate for deposits calculated using available information at time t, and $T_t$ is total transfers from either the government or firms (lump-sum tax or transfer). Lastly, I take the same utility function of New Area Wide Model II where $\kappa$ is habit formation[4]. Coenen et al. (2018) shows that habit formation helps to match the data in the Euro Area better.

Last but not least, the capital stock follows a law of motion with an adjustment cost in changes on investment, as in Christiano et al. (2005).

$$K_t = (1-\delta)K_{t-1} + \left[1 - \frac{\Omega_k}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] I_t \tag{9}$$

## 3.2 Retail Goods Sectors

In this part, I present the production sector that contains two firms, green and brown firms. There are many retailers and each of them produces distinguished retail goods. The retail products are made from one kind of wholesale good which features a constant return to scale technology. Retailers take input prices as given and possess some level of market power in the final product markets. For price setting, we use Rotemberg (1982) with a quadratic cost in a price-setting process. The production technology of a retail good i is provided by:

$$Y_t(i) = \Gamma_t(i), \tag{10}$$

where $Y_t(i)$ is the retail goods for consumption and investment, $\Gamma_t(i)$ is an intermediate inputs combination. From that, the consumption and investment final good is a CES aggregator of all retail products and a demand function of the representative final-good firm

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[3] The two kinds of deposit setup is only to increase tractability, we can understand this as one representative bank with the green and brown lending branch.

[4] Christiano et al. (2005) and Smets and Wouters (2007) show that habit formation helps to capture more realistic consumption dynamics.

for the generic input i is the following:

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}} di\right]^{\frac{\epsilon}{\epsilon-1}} \tag{11}$$

$$Y_t(i) = \left(\frac{p_t(i)}{p_t}\right)^{-\epsilon} Y_t \tag{12}$$

Because the profits for final good producers are zero in equilibrium, it implies the relationship between the price level and retail prices as:

$$P_t = \left[\int_0^1 P_t(i)^{1-\epsilon} di\right]^{\frac{1}{1-\epsilon}} \tag{13}$$

Retailer (i) chooses $P_t(i)$, expressed in terms of the domestic CPI, to maximize her future discounted profit.

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[\frac{P_t(i) - P_{wc,t}}{P_t} Y_t(i) - \frac{AC_t(i)}{P_t}\right] \tag{14}$$

with $p_{wc,t}$ is the price of wholesale goods in terms of the home CPI and can be understood as marginal costs of the retail sector and adjustment costs are defined as follows. A change in retail prices requires quadratic adjustment costs $AC_t(i)$ in nominal term à la Rotemberg (1982) where they change prices with respect to $\bar{\pi}$.

$$AC_t(i) = \frac{\Omega_P}{2} \left(\frac{P_t(i)}{P_{t-1}(i)} - \bar{\pi}\right)^2 Y_t \tag{15}$$

## 3.3 Wholesale and Intermediate Goods Sectors

The intermediate goods sector includes green and brown firms. Both kinds of firms are modelled under the spirit of Bernanke et al. (1999) (BGG) environment. In the wholesale sector, we combine two kinds of intermediate goods from green and brown firms. $\Gamma_t$ denotes the number of wholesale goods while $Y_{G,t}$ and $Y_{B,t}$ are green firms and brown firms output, respectively. A composition for wholesale goods is given as:

$$\Gamma_t = (\phi Y_{G,t}^{\frac{\sigma-1}{\sigma}} + (1-\phi) Y_{B,t}^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}} \tag{16}$$

where $\sigma > 0$ is the elasticity of substitution between green firms and brown firms' goods and $\phi \in (0,1)$ is the share of green firms' goods in the wholesale bundle. Cost-minimization implies:

$$Y_{G,t} = \phi^{\sigma} \left( \frac{p_{G,t}}{p_{wc,t}} \right)^{-\sigma} \Gamma_t, Y_{B,t} = (1-\phi)^{\sigma} \left( \frac{p_{B,t}}{p_{wc,t}} \right)^{-\sigma} \Gamma_t \tag{17}$$

We define $p_{G,t}$ and $p_{B,t}$ as prices of green firms' goods and brown firms' goods relative to consumption units, respectively. Finally, zero earnings in the wholesale sector imply a composition of prices:

$$p_{wc,t} = (\phi^{\sigma} p_{G,t}^{1-\sigma} + (1-\phi)^{\sigma} p_{B,t}^{1-\sigma})^{\frac{1}{1-\sigma}} \tag{18}$$

Equilibrium conditions of firms are derived below with two sectors, $i = G, B$, which stands for green and brown firms. We assume that both representative firms in the intermediate goods sectors share identical production technology. The difference lies in their working capital constraints. Both firms face working capital constraints and have to pay wages and rental payments through external debts and internal net worth. However, brown firms need to pay an extra cost for tax on their carbon emission and abatement costs to reduce their emission. Following Bernanke et al. (1999), there is a costly state verification problem for obtaining funds from the financial sector. Each firm in sector i produces an identical intermediate good $Y_{it}$ from capital $K_{it}$ and two kinds of labour inputs including entrepreneurial labour $H^e_{it}$ and households labour $H_{it}$, with a homogeneous Cobb-Douglas production function for both types of firms.

$$Y_{it} = A_{it}^{env} \omega_{it} K_{it}^{1-\alpha} [(H^e_{it})^{1-\theta} (H_{it})^{\theta}]^{\alpha}, \tag{19}$$

$A_{it}$ denotes a sector-specific productivity shock to all firms that operate in sector i. Moreover, $\alpha \in (0,1)$ is the input elasticity between capital and total labour. $\theta \in (0,1)$ is the input elasticity between two kinds of labour types, household labour and entrepreneurial labour. Besides, $\omega_{it}$ is an idiosyncratic productivity shock for each firm in sector i, and it is assumed to be an i.i.d. process over firms and time. For simplicity, we assume that the $F(\cdot)$ is a non-negative support distribution from which an idiosyncratic productivity shock is drawn. This distribution is identical for both sectors. There is not much evidence that using different distributions can cause immense differences or match the data better. Following Chang et al. (2019), the idiosyncratic productivity shocks are distributed following a Pareto distribution in which the cumulative density function has the form as $F(\omega) = 1 - (\frac{\omega_m}{\omega})^k$ over the range $[\omega_m, \infty)$ with $\omega_m$ and $k$ being the scale and shape parameters, respectively. Both kinds of productivity shocks follow a standard AR(1) process.

$$A_t^{env} = \left(1 - \left(d_0 + d_1\, X_t + d_2\, X_t^2\right)\right) A_t \tag{20}$$

$$\log(A_t) = (1 - \rho_a)\, \log(A) + \rho_a\, \log(A_{t-1}) + \epsilon_t^A, \quad \epsilon_t^A \sim \mathcal{N}(0,\, \sigma_a^2) \tag{21}$$

Equation 21 describes the law of motion of productivity as an AR(1) process with steady-state $A$, persistence $\rho_a$ and standard deviation $\sigma_a$. The carbon stock can be accumulated by total domestic emissions, $e_t$ and the rest of the world (ROW) emissions, $e_t^{row}$. For a closed economy, ROW emissions are exogenous. Domestic emissions are emitted through the production of intermediate goods. We assume that a fraction $\mu_t$ of emissions is abated by firm i. Thus, the abatement cost $(z_t)$ is defined as an increasing function of the output of firm i. Because all intermediate firms choose the same (optimal) price, inputs and output, the equilibrium conditions hold without index i. Hence, total pollution, emissions, and abatement costs are given by:

$$X_t = \eta\, X_{t-1} + e_t + e_t^{row} \tag{22}$$

$$e_t = \gamma_1\, (1 - \mu_t)\, Y_{B,t} \tag{23}$$

$$z_t = \theta_1\, \mu_t^{\theta_2}\, Y_{B,t} \tag{24}$$

Lastly, the operation of all firms is subjected to constraints. Thus, they have to pay wages and capital rent beforehand. These amounts are paid by using their net worth at the beginning and by borrowing from financial intermediates. From the BGG, the initial net worth is usually small and firms rely on external loans heavily. Hence, the constraint for working capital in sector i is set differently for brown and green firms.

For green firms, they have to pay wages and capital costs for their operation.

$$N_{G,t-1} + B_{G,t} = w_t H_{G,t} + w^e_{G,t} H^e_{G,t} + r^k_t K_{G,t} \tag{25}$$

Brown firms have to pay additional abatement costs and carbon prices for their emission.

$$N_{B,t-1} + B_{B,t} = w_t H_{B,t} + w^e_{B,t} H^e_{B,t} + r^k_t K_{B,t} + \underbrace{\theta_1 \mu_t^{\theta_2} Y_{B,t}}_{z_t} + \tau^e_t \underbrace{(1-\mu_t)\gamma_1 Y_{B,t}}_{e_t} \tag{26}$$

where $N_{i,t-1}$ is the beginning-of-period net worth, $w_t$ and $w^e_{it}$ denote the real wage rate of household labour and managerial labour in the sector i, respectively. $B_{i,t}$ is external debt as in Bernanke et al. (1999).

## 3.4 Green and Brown Financial Intermediates

For financial intermediaries, both green and brown loans are subject to the macroprudential policy in the form of reserve requirements[5]. We assume a representative bank for simplicity and assume identical commercial banks where the heterogeneity only lies in the type of loans.

Following BGG, if firms realize that their idiosyncratic productivity level is sufficiently low, they choose to go bankrupt. As a result, in every period, some firms go bankrupt, which makes bank loans suffer from default risk. Loans are subject to the heterogeneous macroprudential tax in terms of reserve requirement which can be used later for our policy analysis and creates a wedge between the green firms' loan rate and the deposit rate. $\tau^i_t$ is the reserve requirement ratio.

$$(r_{G,t} - 1)(1 - \tau^G_t) = r_t - 1 \tag{27}$$

$$(r_{B,t} - 1)(1 - \tau^B_t) = r_t - 1 \tag{28}$$

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[5] The financial sector can contain many competitive commercial banks

For green firms, due to the default risk, banks need to charge a higher contractual interest rate $Z_{G,t}$ on all risky loans to handle expected monitoring and liquidation costs in case of bankruptcy. This is known as a state-contingent gross interest rate. As in BGG, firms go bankrupt if their realized productivity is below a threshold productivity level $\bar{\omega}_{G,t}$, where $\bar{\omega}_{G,t}$ satisfies:

$$\bar{\omega}_{G,t} = \frac{Z_{G,t} B_{G,t}}{\tilde{A}_{G,t}(N_{G,t-1} + B_{G,t})} \tag{29}$$

in which the term $\tilde{A}_{G,t}$ can be considered as the rate of return for the firm's portfolio which is balanced by borrowing and internal funds.

$$\tilde{A}_{G,t} = p_{G,t} A_{G,t} \left(\frac{1-\alpha}{r_t^k}\right)^{1-\alpha} \left[\left(\frac{\alpha(1-\theta)}{w_{G,t}^e}\right)^{1-\theta} \left(\frac{\alpha\theta}{w_t}\right)^{\theta}\right]^{\alpha} \tag{30}$$

The maximization problem is as follows where $f(\bar{\omega}_{G,t})$ and $g(\bar{\omega}_{G,t})$ are defined as the share of firms income in sector i for the owner and the lender, respectively:

$$\max \tilde{A}_{G,t}(N_{G,t-1} + B_{G,t}) f(\bar{\omega}_{G,t}) \tag{31}$$

where firms are subject to a lender's incentive constraint.

$$\tilde{A}_{G,t}(N_{G,t-1} + B_{G,t}) g(\bar{\omega}_{G,t}) \geq r_{G,t} B_{G,t} \tag{32}$$

Following Bernanke et al. (1999), the relationship between the productivity cut-off and the leverage ratio, which follows the optimal contract maximization problem is given as :

$$\frac{N_{G,t-1}}{N_{G,t-1} + B_{G,t}} = -\frac{g'(\bar{\omega}_{G,t})}{f'(\bar{\omega}_{G,t})} \frac{\tilde{A}_{G,t} f(\bar{\omega}_{G,t})}{r_{G,t}} \tag{33}$$

Last but not least, the aggregate net worth of firms in each sector at the end of period t includes profits of surviving firms and the entrepreneur's salary (income) in that sector where $\delta_G$ is the survival rate of a manager. For tractability, we do not entail the entry and exit problem or include the entrepreneur explicitly. Hence, each manager provides one unit of labour and the entrepreneurial labour is distinguished between sectors ($H^e_{Gt} = 1$).

$$N_{G,t} = w^e_{G,t} H^e_{G,t} + \delta_G \tilde{A}_{G,t}(N_{G,t-1} + B_{Gt}) f(\bar{\omega}_{Gt}) \tag{34}$$

For the brown firms, the problem is more complicated due to the cost paid for their emission. For simplicity, we define emission cost as follows:

$$cost^E_t = \frac{\theta_1(\mu_t)^{\theta_2} y^B_t + \tau^e_t (1 - \mu_t)\gamma_1 y^B_t}{\tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})} \tag{35}$$

Due to the default risk, banks need to charge a higher contractual interest rate $Z_{B,t}$

$$\bar{\omega}_{B,t} = \frac{Z_{B,t} B_{B,t}}{\tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})(1 - cost^E_t)} \tag{36}$$

in which the term $\tilde{A}_{B,t}$ can be considered as the rate of return for the firm's portfolio which is balanced by borrowing and internal funds.

The maximization problem is as follows where $f(\bar{\omega}_{B,t})$ and $g(\bar{\omega}_{B,t})$ are defined as the share of firm income in sector B for the owner and the lender, respectively:

$$\max \tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})(1 - cost^E_t) f(\bar{\omega}_{B,t}) \tag{37}$$

where firms are subject to a lender's incentive constraint.

$$\tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})(1 - cost^E_t) g(\bar{\omega}_{B,t}) \geq r_{B,t} B_{B,t} \tag{38}$$

Following Bernanke et al. (1999), the relationship between the productivity cut-off and the leverage ratio, which follows the optimal contract maximization problem is given as :

$$\frac{N_{B,t-1}}{(N_{B,t-1} + B_{B,t})(1 - cost^E_t)} = -\frac{g'(\bar{\omega}_{B,t})}{f'(\bar{\omega}_{B,t})} \frac{\tilde{A}_{B,t} f(\bar{\omega}_{B,t})}{r_{B,t}} \tag{39}$$

Lastly, the aggregate net worth of firms at the end of period t takes the following form.

$$N_{B,t} = w^e_{B,t} H^e_{B,t} + \delta_B \tilde{A}_{Bt}(N_{B,t-1} + B_{B,t})(1 - cost^E_t) f(\bar{\omega}_{B,t}) \tag{40}$$

### 3.5 Central Banks and Market Clearing

The central bank controls the standard Taylor rule and macroprudential tools for the green and brown sectors.

$$\ln\left(\frac{R_t}{R_{ss}}\right) = \rho_r ln\left(\frac{R_{t-1}}{R_{ss}}\right) + (1-\rho_r)\left(\rho_\pi ln\left(\frac{\pi_t}{\pi_{ss}}\right) + \rho_y ln\left(\frac{GDP_t}{GDP_{t-1}}\right)\right) \tag{41}$$

$$\tau_t^G = \tau_{ss}^G \tag{42}$$

$$\tau_t^B = \tau_{ss}^B \tag{43}$$

In equilibrium, all markets are clear. First, the final goods market clearing condition is given:

$$\begin{aligned} Y_t = C_t + I_t + G_t + \theta_1(\mu_t^{\theta_2})y_{B,t} + \frac{\kappa_P}{2}(\pi_t - \bar{\pi})^2 Y_t + \tilde{A}_{G,t}(\frac{n_{G,t-1}}{\pi_t} + b_{G,t})m_g \int_0^{\omega_{\bar{G},t}} \omega\, dF(\omega) \\ + \tilde{A}_{B,t}(\frac{n_{B,t-1}}{\pi_t} + b_{B,t})(1 - cost_t^E)m_b \int_0^{\omega_{\bar{B},t}} \omega\, dF(\omega) \end{aligned} \tag{44}$$

where $G_t$ stands for autonomous government spending. Capital and labour market clearing imply:

$$K_{t-1} = K_{G,t} + K_{B,t}, \tag{45}$$

$$H_t = H_{G,t} + H_{B,t} \tag{46}$$

The loan-able funds market with reserve requirement clearing implies:

$$\frac{B_{G,t}}{(1-\tau_t^G)} = D_t^G \tag{47}$$

$$\frac{B_{B,t}}{(1-\tau_t^B)} = D_t^B \tag{48}$$

Finally, GDP takes the form below without liquidation cost and adjustment cost for simplicity.

$$GDP_t = C_t + I_t + G_t \tag{49}$$

where the government can finance public expenditure $G_t$ by raising lump-sum and emission taxes. Environmental tax is implemented through a shock process[6].

$$\begin{aligned} G_t &= T_t + \tau_t^e e_t \\ \tau_t^e &= (1 - \rho_e)\tau_{ss}^e + \rho_e \tau_{t-1}^e + \epsilon_t^e \end{aligned}$$

## 3.6 Calibration and Model Validation

The model is calibrated following Euro Area data and follows New Area Wide Model-II (NAWM-II). I try to match the key steady-state ratio of the Euro Area. All banking sector-related parameters will follow Leduc and Natal (2017) and Bernanke et al. (1999) for key parameters. The proportion of businesses going bankrupt is set at 3% annually. Hence, the entrepreneur's survival probability (from one quarter to the next), is set to 0.97, in line with Bernanke et al. (1999). The bank's monitoring cost as a share of the final output is 0.15.

The main purpose of this work is to focus on a specific scenario that is yet to happen. However, in this section, I also demonstrate that our model performs well in replicating the statistical patterns and relationships among key economic variables in the Euro Area. This is aimed to show that I analyze with a proper business cycle model.

To accomplish this, I solve the model using a first-order approximation and simulate a Total Factor Productivity (TFP) shock. As a reference point, I compare the model's results to the actual business cycle data for the Euro Area from 1999Q1 to 2019Q4, encompassing the period from the establishment of the Euro Area to just before the onset of the pandemic. I calibrate the magnitude of TFP shocks to make our standard deviation match the standard deviation of Euro Area GDP, which is 1.14%.

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[6] Heutel (2012) show that carbon price and cap and trade provide quite similar results in the theoretical model.

| Parameter | Description | Value | Notes |
|---|---|---|---|
| $\beta$ | Discount factor | 0.9988 | Real rate of 2% annually (NAWM-II) |
| $\varphi$ | Inverse of Frisch elasticity | 2 | NAWM-II |
| $\varsigma$ | Habits | 0.8 | To match moments |
| $\varepsilon$ | Elas. of subst. differentiated goods | 3.8571 | NAWM-II |
| $1-\alpha$ | Share of capital in production | 0.3530 | $\frac{i}{y} = 0.21(\mathrm{NAWM-II})$ |
| $\kappa_P$ | Price adjustment costs | 71.2043 | NAWM-II (Calvo parameter) |
| $\delta$ | Depreciation rate | 2.5% | NAWM-II |
| $\kappa_I$ | Investment adjustment cost | 10.78 | NAWM-II |
| $\pi$ | SS inflation | 1.005 | ECB target |
| $\tilde{g}$ | Public spending | 0.1075 | $g/y = 0.215$ (NAWM-II) |
| $\phi_\pi$ | Taylor rule coefficient | 2.74 | NAWM-II |
| $\phi_y$ | Taylor rule coefficient | 0.1 | NAWM-II |
| $\rho_r$ | Inertia of Taylor rule | 0.93 | NAWM-II |
| $\theta$ | Weight of brown good | 0.68 | Giovanardi et al. (2023) |
| $\sigma$ | Elas. of subst. brown-green good | 2 | Papageorgiou et al. (2017) |
| $\delta_x$ | Pollution depreciation | 0.0035 | Gibson and Heutel (2020) |
| $\tilde{e}^{row}$ | Emissions in the rest of the world | 2.7955 | $\frac{e^{\mathrm{row}}}{e} = 15.31$ |
| $\gamma_1$ | Shifter in the emission function | 0.499 | Estimated in Ferrari and Pagliari (2021) |
| $\theta_1$ | Coefficient in the abatement function | 0.0335 | Gibson and Heutel (2020) |
| $\theta_2$ | Coefficient in the emission function | 2.6 | Gibson and Heutel (2020) |
| $\tau^G, \tau^B$ | Steady-State reserve requirement | 0.02 | Leduc and Natal (2017) |
| $\rho_a$ | AR(1) TFP parameter | 0.91 | To match the stand. dev. of EA output |
| $\sigma_a$ | Stand. dev. of TFP shock | 1.14% | To match the stand. dev. of EA output |

**Table 1:** Calibration for Euro Area

Using only TFP shocks, the model is able to replicate important statistical characteristics well (as shown in Table 2). For instance, it correctly reflects that consumption and inflation are less volatile than output, while investment is more volatile. Although the model predicts a slightly less volatile investment, it matches other factors well. Additionally, it captures the strong correlations between consumption, investment, and output, as well as the autocorrelation of output. Naturally, adding more shock processes can help to increase the fit of the model but it is not our main focus[7]. In the Appendix, I also plot the impulse response function of TFP shock in Figure 18. The impulse responses are in line with the New Keynesian literature, both the standard one (Coenen et al. (2018) for the Euro Area) and the environmental one (Annicchiarico and Di Dio (2015)).

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[7] Our model is rich enough for more shock processes.

|  |  | $GDP_t$ | $C_t$ | $I_t$ | $\Pi_t$ |
|---|---|---|---|---|---|
| Standard deviation (in %) | Data | 1.19 | 0.66 | 2.85 | 0.28 |
|  | Our Model | 1.19 | 0.65 | 2.55 | 0.28 |
| Standard deviation relative to GDP | Data | 1 | 0.55 | 2.39 | 0.23 |
|  | Our Model | 1 | 0.55 | 2.1 | 0.23 |
| Correlation with GDP | Data | 1 | 0.83 | 0.84 | 0.42 |
|  | Our Model | 1 | 0.97 | 0.99 | 0.21 |
| Autocorrelation | Data | 0.90 | 0.90 | 0.68 | 0.22 |
|  | Our Model | 0.94 | 0.93 | 0.95 | 0.53 |

**Table 2:** The dataset includes seasonal adjusted GDP, consumption, investment, and CPI inflation in the Euro Area, processed using the HP filter with a smoothing parameter of 1600. The data covers the period from 1999Q1 to 2019Q4 and is taken from Eurostat.

# 4 Numerical Simulation

In this part, I study the 3 different scenarios of imposing an ambitious carbon price for our economy. In the first scenario, I impose an unanticipated hike in carbon price in the 5th to cut emissions by 40% immediately. This can be interpreted as an overnight carbon price introduction. In the second scenario, I observe a well-communicated commitment to carbon policy that increases linearly for 30 years to reach a zero economy by 2050. Lastly, I discuss the effect of pre-announcement on an ambitious carbon price. This includes a ”forward guidance” carbon policy and a linear increase in carbon price since the 1st period.

## 4.1 Unanticipated Introduction of Climate Policy

In this section, I conduct a similar scenario as presented by Carattini et al. (2021). We introduce an unanticipated carbon shock in the 5th period, where the government decides to implement a necessary carbon price hike to achieve a 40% reduction of emissions in 2030, following the suggestion by the International Monetary Fund (IMF). The assumption is that the carbon price increase is introduced without prior communication to the public, thus creating an unanticipated shock to the economy.

To analyze the effects of this unanticipated carbon shock, I examine the transition dynamics that occur after the introduction of the carbon price. We specifically emphasize the role of the banking sector in the impact of carbon prices. It is important to note that the suggested reduction of 40% by the IMF (2020) is set to be achieved in 2030, which is approximately

8 years from now. However, for illustration purposes, I present the unanticipated shock in the 5th period[8].

Figure 4 illustrates the impulse response functions (IRFs) of a carbon price hike aimed at achieving a 40% reduction in emissions. In the model with banking sectors, output experiences a decrease of 0.7%. In the model without banking sectors, the decrease is slightly smaller at 0.5%. My finding differs from Dück and Le (2023), which suggests a relatively quick return to a new steady state. Our model with two sectors captures the substitution effect between the sectors, which takes longer to reach the new steady state.

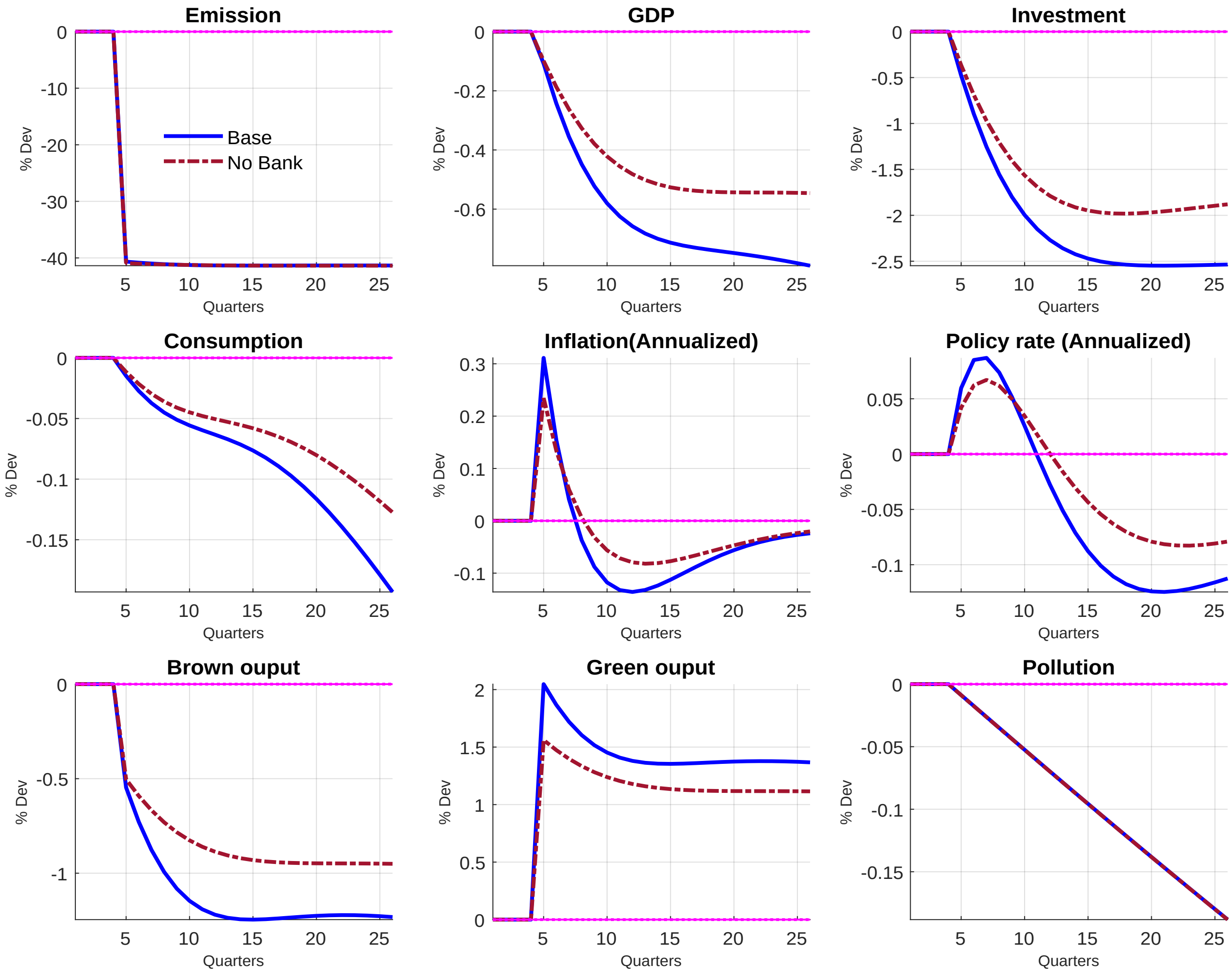

**Figure 4:** The impulse response of an unanticipated shock after 5 periods. Time is in quarters. Impulse responses are in percentage deviation from steady states. The blue line is our Base model with banking sectors. The red dashed line is the model without banking sectors.

During the simulation, we observe a decrease in consumption of 0.2% and 0.15% in the

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[8] I assume that there is no shock in the first few periods so the effect for unanticipated shock is identical either in the 5th period or 25th period.

Base and No-bank versions, respectively. Similarly, investment exhibits a similar pattern, declining by 2.5% and 1.5% in the Base and No-bank versions. These results align with stylized facts indicating that consumption tends to be more persistently affected compared to output, and investment reacts more strongly to transition shocks as it directly impacts capital and investment demand.

The carbon price increase leads to an annualized inflationary effect of 0.3% after 7 periods, consistent with our empirical evidence and the concept of "greenflation." The carbon price policy directly impacts firms' cost structure, resulting in price level increases and subsequent inflationary pressures. Consequently, the interest rate initially peaks at 0.07% after 8 periods due to inflation and output movements. However, the interest rate gradually declines after 15 periods, eventually returning to levels around 0 from below.

The introduction of the carbon price aims to internalize the costs associated with climate change and reduce carbon emissions. This demand reduction subsequently leads to a decrease in output. In the case of an unanticipated introduction of the carbon price, the supply-side effects appear to dominate in the initial periods. The increase in marginal costs following the carbon price hike contributes to higher inflation rates. However, over time, households internalize the permanent effect of the carbon price, and demand reaches its lowest point, leading to a small deflationary effect[9].

Indeed, the graph clearly illustrates the amplification effect of the banking sectors during the transition to a low-carbon economy. As expected, the banking sectors play a significant role in propagating the effects of the carbon price policy. The drop in profits and net worth of brown firms contributes to an increase in the counter-cyclical external finance premium. This leads to higher default risk and a widening spread for brown banks, reflecting the financial instability consequences of the carbon policy shock.

Interestingly, the study finds a strong substitution effect in the green sector, which contrasts with the findings of Carattini et al. (2021). This suggests that the absence of an optimal portfolio problem in the banks allows them to allocate their funds more easily to green sectors, promoting a shift towards greener investments. Overall, these results highlight the

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[9] It is important to note that the simulation aims to shift the entire economy to a new steady state, reflecting the long-term effects of the carbon price policy and the transition to a more sustainable and low-carbon economy.

importance of considering the role of banking sectors in the context of carbon pricing and transition risk. The financial sector's response to carbon policy shocks can significantly impact the overall economic outcomes and the transition to a low-carbon economy. Hence, this gives rise to the need for heterogeneous credit policies for each sector.

Compared to the model in Carattini et al. (2021), this paper makes two significant contributions to the study of transition risk. First, it investigates transition risk within a New Keynesian model that incorporates inflation and monetary policy. It is worth noting that monetary policy holds a crucial role in the business cycle model and remains a powerful tool for central banks. Additionally, both this paper and Carattini et al. (2021) primarily focus on macroprudential policy. Nevertheless, it is highly important to examine the interaction between macroprudential policy and monetary policy, particularly when these two tools target different objectives.

Secondly, this paper adopts a different framework for the financial sector and financial frictions. The rationale behind this choice is the source of transition risk, which naturally stems from the production sectors responsible for most GHG emissions. Carattini et al. (2021) place financial frictions in the context of moral hazard between households and banks, where the source of transition risk originates from the production sector. In this paper, I directly address this issue by positing that the moral hazard problem occurs between banks and firms. The carbon price directly impacts the firm's balance sheet, which, in turn, affects its credit profile in the financial market. While both papers identify an amplified effect within the banking sector, the mechanisms behind this observation are quite different. In Carattini et al. (2021), the amplified effect can be traced back to the reduction in asset prices and investments following a decrease in capital demand from the production sector. In our model, the amplified effect results from the carbon price reducing the revenue of the brown sector and increasing borrowing costs. This leads to differences in the dynamic responses of the two papers.

To better understand the financial sector, Figure 16 illustrates the financial variables of the green and brown sectors. As the substantial carbon tax affects the brown sector, it also leads to an increase in the brown borrowing rate. This is reflected through the credit spread of the brown sector. As the demand shifts to green goods, the net worth of green entrepreneur increases following their revenue. Simultaneously, the lower cost of borrowing encourages green firms to borrow more to expand their businesses in response to the increased demand for green goods, as reflected in the rise in green loans. However, the total credit in the economy decreases significantly, giving rise to the effects of macroprudential policy later.

## 4.2 Toward Zero-Emission Economy in 2050

Reaching a zero-emission economy is a significant long-term goal for both developed and emerging market economies. In this scenario, the paper introduces a linearly increasing carbon price with perfect foresight, aiming to achieve a zero-emission economy after 30 years. This approach is similar to the one adopted by Ferrari and Nispi Landi (2023). By imposing a perfect foresight carbon price trajectory, the model captures the gradual transition towards a sustainable economy. This scenario allows for an analysis of the long-term effects and implications of climate policy. It provides insights into the potential challenges and adjustments that the economy may face over the next 30 years.

From Figure 5, one can observe that the introduction of a gradually increasing carbon price aimed at achieving a zero-emission economy after 30 years has varying effects on consumption and investment. In the short term, there is a small-scale boost in consumption as households anticipate the future trajectory of the carbon policy shock and choose to shift their consumption forward. However, investment does not experience the same boost and remains relatively unaffected. In terms of output and investment, there is a gradual decline that accelerates from period 5 onwards. This reduction in output and investment results from the expected higher costs associated with transitioning to a clean economy. Over the 30-year period, the analysis indicates a permanent loss of 4% in output to achieve the goal of a zero-emission economy.

Comparing this scenario to the one with a 40% reduction, the zero-emission scenario leads to a deeper and more prolonged recession. However, macroeconomic variables respond more slowly in the initial periods due to firms anticipating higher costs in the future and, consequently, producing more in the short term. Investment is particularly affected, experiencing a decline of 5% after 25 years. Even after 50 years, a clear recovery is not evident, with a gradual improvement in total factor productivity (TFP) levels being the primary source of a negligible rebound. Regarding inflation and interest rates, the zero-emission scenario predicts a deflationary effect and a reduction in interest rates. However, both variables gradually return to zero as the price level adjusts over time.

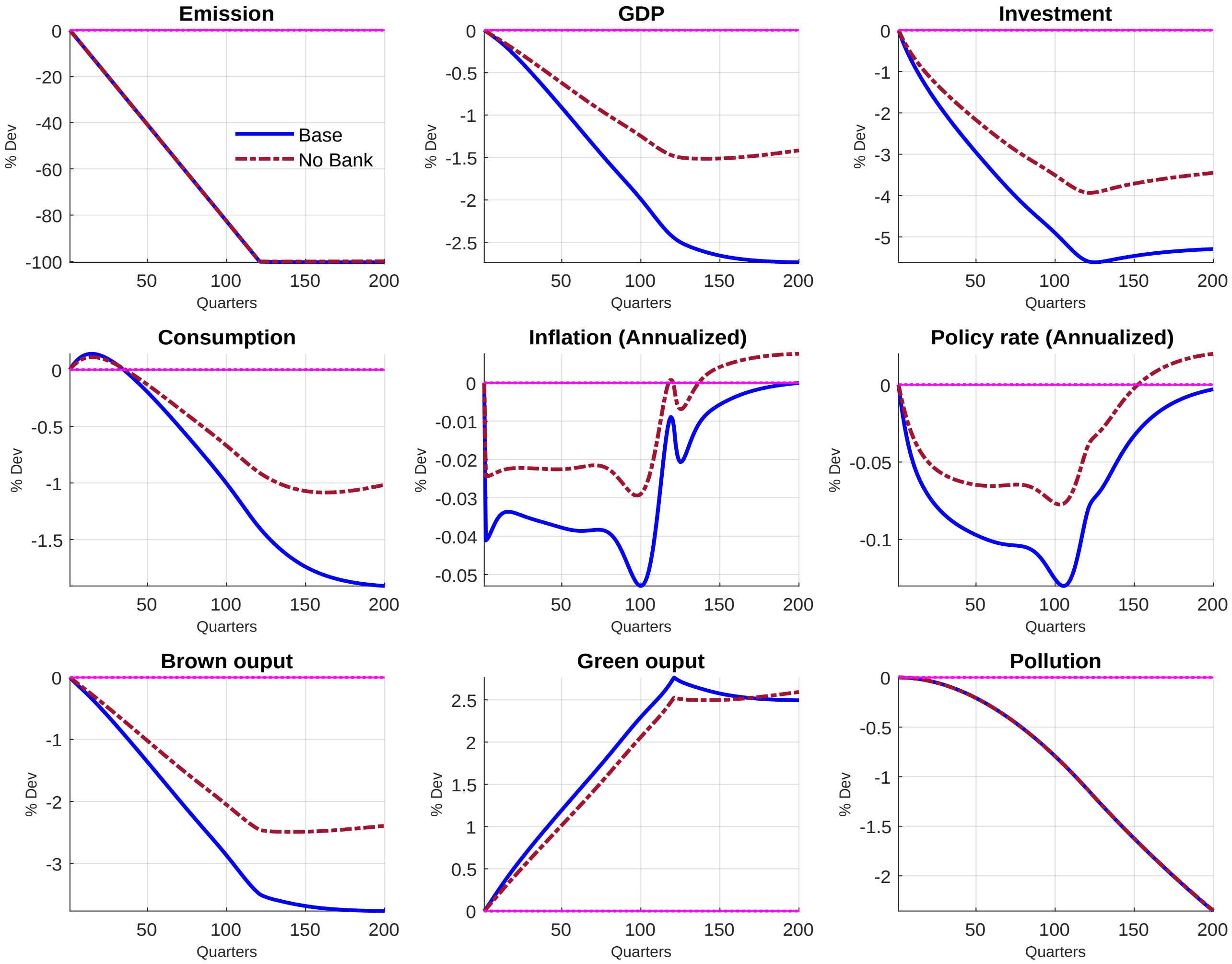

**Figure 5:** The impulse response of a linearly increasing carbon price to archive zero-emission after 30 years. Time is in quarters. Impulse responses are in percentage deviation from steady states. The blue line is our Base model with banking sectors. The red dashed line is the model without banking sectors.

Indeed, the analysis of the inflationary effect of the green transition aligns with the findings of Ferrari and Nispi Landi (2023). Our results regarding inflation also corroborate the study of the inflationary effect of green transition in Ferrari and Nispi Landi (2022). The implementation of a carbon price hike increases marginal costs, leading to an inflationary effect from the supply side. However, when households anticipate the carbon policy from the beginning, their decreased demand outweighs the impact of higher marginal costs, resulting in a decrease in the inflation rate. Firms, being forward-looking, also take into account the anticipated policy and adjust their prices to maximize profits before the costs associated with emissions become more significant. Consequently, the model still predicts a deflationary effect despite the initial inflationary pressure caused by the carbon price hike. In the Appendix, Figure 17 depicts the transition of financial sector variables. Notably, the net worth and credit spread of the brown sectors exhibit a much larger impact compared to the green sectors over a 30-year period.

These results emphasize the importance of forward-looking behaviour by households and firms in shaping the overall inflationary dynamics during the transition to a green economy. By incorporating expectations and adjusting their behaviour accordingly, economic agents play a crucial role in determining the inflationary effects of climate policies.

## 4.3 Anticipated Carbon Policy

In this part, I study the effect of a well-communicated carbon policy. In Section 4.1, I introduced what is called an overnight policy, which is not realistic. It is natural to ask how the communication of our ambitious carbon policy affects its economic effect. Hence, I compare the pre-announcement of the carbon policy 4 periods ahead to the overnight carbon policy introduction in Figure 6.

As expected, the household is strongly forward-looking and adjusts its demand from the very beginning. This creates a negative demand shock type before the carbon policy takes effect. We note that the inflation dynamic is affected strongly. Hence, the policy rate reacts much less and decreases quickly to support the output. From this simulation, we observe a strong reaction in inflation when comparing the anticipated and unanticipated introduction. Hence, it is natural to ask how strong the effect of preannouncement is. In the next section, I will vary the time horizon ahead of the introduction of an ambitious carbon price.

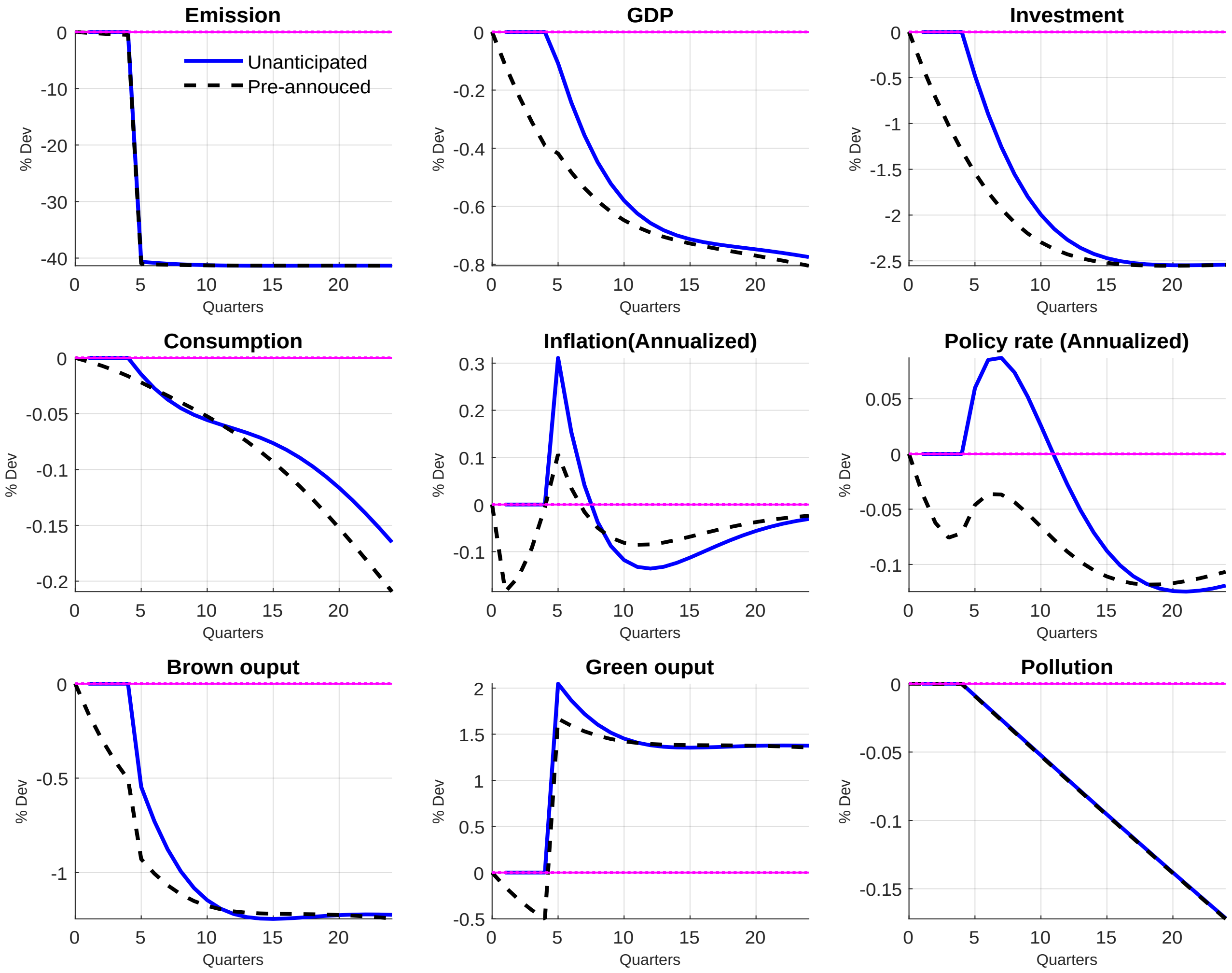

**Figure 6:** The impulse response of a carbon price hike with the pre-announcement policy from the 0th period and take effect in the 5th period. Time is in quarters. Impulse responses are in percentage deviation from steady states. The blue line is an unanticipated carbon price hike, the dashed black line is the pre-announcement policy.

### 4.3.1 "Forward Guidance" of Carbon Policy

Building on the literature on forward guidance and its effects on output and inflation expectations, I investigate three cases of introducing the carbon policy in the 1st, 5th, and 10th periods. However, it is important to note that households perfectly anticipate the policy from period 0. In all three cases, we observe that the economy starts to react immediately, regardless of when the carbon policy is implemented. This suggests that the forward-looking behaviour of households plays a crucial role in shaping the economic response to climate policies, emphasizing the importance of considering expectations and communication in policy design and implementation.

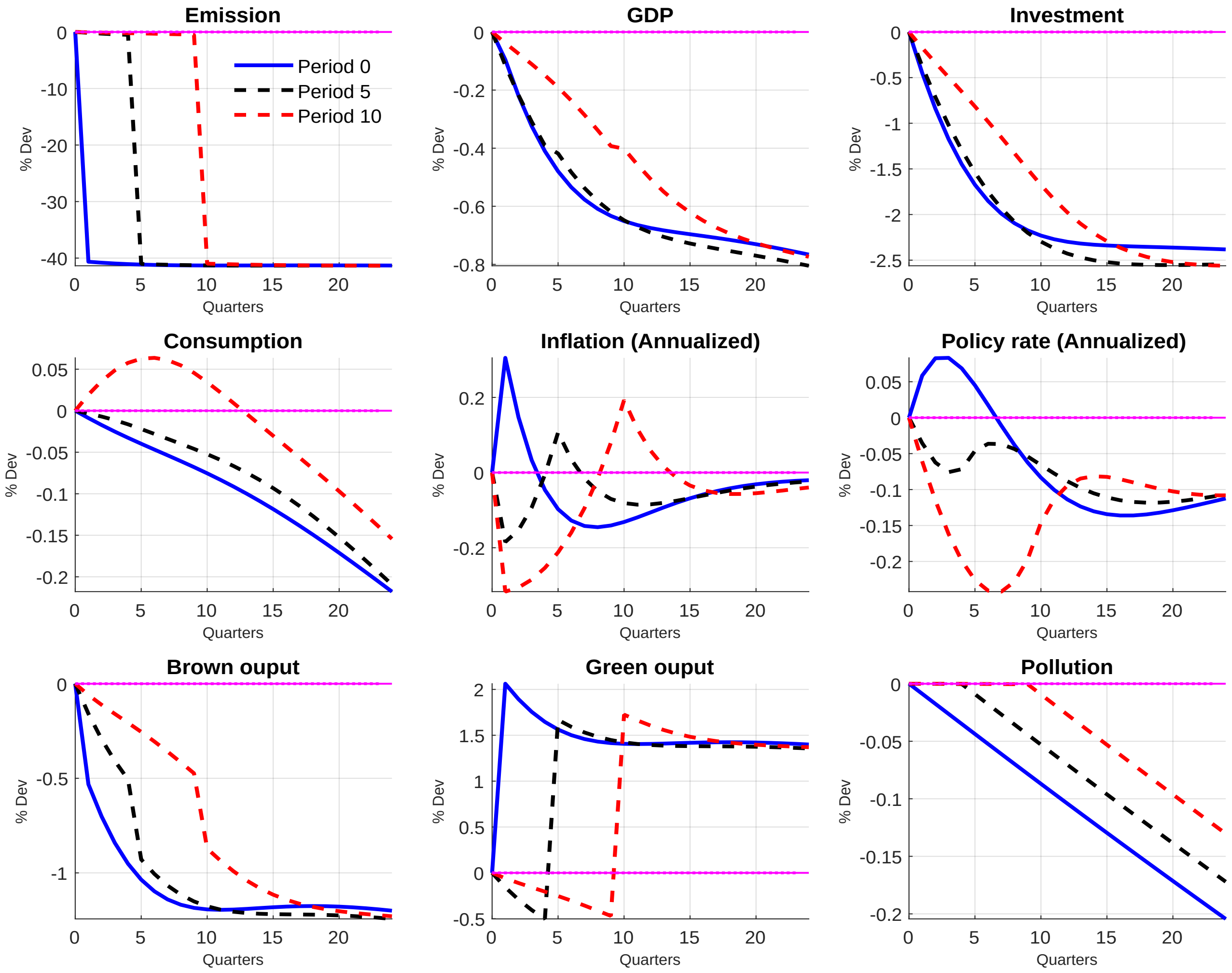

**Figure 7:** The impulse response of an anticipated shock in the 1st, 5th and 10th period. Time is in quarters. Impulse responses are in percentage deviation from steady states. All the scenarios are perfectly anticipated from period 0. The blue line is the carbon policy implemented in period 1. The dashed black line is the carbon policy implemented in period 5. The dashed red line is the carbon policy implemented in period 10.

We observe that if the households believe in the commitment to environmental policy, they take into account the future drop in output and income. This leads to a strong decrease in consumption and investment in the current period. Within our model, compared to the other two scenarios, we observe that the design of environmental policy affects the inflation dynamic significantly. With an unanticipated introduction of a carbon price hike, the marginal cost effect seems to dominate as the households' demand takes some time to adjust. In the anticipated one-time introduction, the households cut back their consumption and investment as they anticipated the hike in carbon price in the 5th period. However, if the carbon price does not increase linearly for a long period, the supply side outranks the demand at some point. Thus, we see an inflationary effect before the price level stabilizes.

### 4.3.2 Now or Later

In Figure 4, I simulate an unanticipated carbon policy price hike. Because it is fully unanticipated, it is not the case in reality when any kind of policy might be communicated well before implementation. Hence, it is an interesting question to ask if we should implement the carbon price sooner but with a well-communicated path. In Figure 8, I shed some light on that question. I keep our target of a 40% reduction in emissions but I impose a linearly increasing carbon tax for 24 periods to match the emission target of 40% emission reduction in 2030. I also include the case where the policymaker communicates their carbon hike in period 25 at period 0. The results show many interesting findings. First, I also observe the overall recessionary effect. However, consumption increases in the first few periods as the household perfectly anticipated the path of the carbon price. They shift their consumption forward. This effect is even stronger in the case of the pre-announcement of the carbon price. I also see a shift in investment in both cases but the effect is small. In terms of inflation, the inflation dynamic shows significant differences. There is mostly a deflationary effect for linear and pre-announcement cases. For the pre-announcement case, the peak of inflation is smaller when the carbon policy takes effect in the 25th period.

Notably, we observe a decrease in the production of green firms a few periods ahead of the carbon price hike. This is mostly driven by the drop in demand which starts before the carbon policy is materialized. Moreover, the peak of increase for green output is less than the unanticipated case. It seems like if we act now with a linearly increased carbon price, the effect is more severe as the economy has to suffer for a long shock that increases every day. However, the pre-announcement seems to be a good solution as it can act as a stimulus for the economy in the first few periods. The results are different compared to Dück and Le (2023) with only 5 periods ahead of the policy implementation. This suggests the macroeconomic effects depend crucially on the period ahead of the announcement or the time that the economy has to suffer from linearly increasing carbon prices. However, I also document the reduction in inflation volatility in the ”forward guidance” carbon price and the linearly increasing carbon price.

Lastly, I also investigate the role of the green sector in Figure 11 and Figure 12. Firstly, we can achieve the climate target with a significantly lower economic cost when the green sector is immense. The results are as expected since a larger green sector means fewer emissions need to be cut. Hence, investment in expanding the green sector is highly necessary to deal with transition risk. Secondly, we find that a higher elasticity of substitution between the two sectors leads to a more severe response to transition risk.

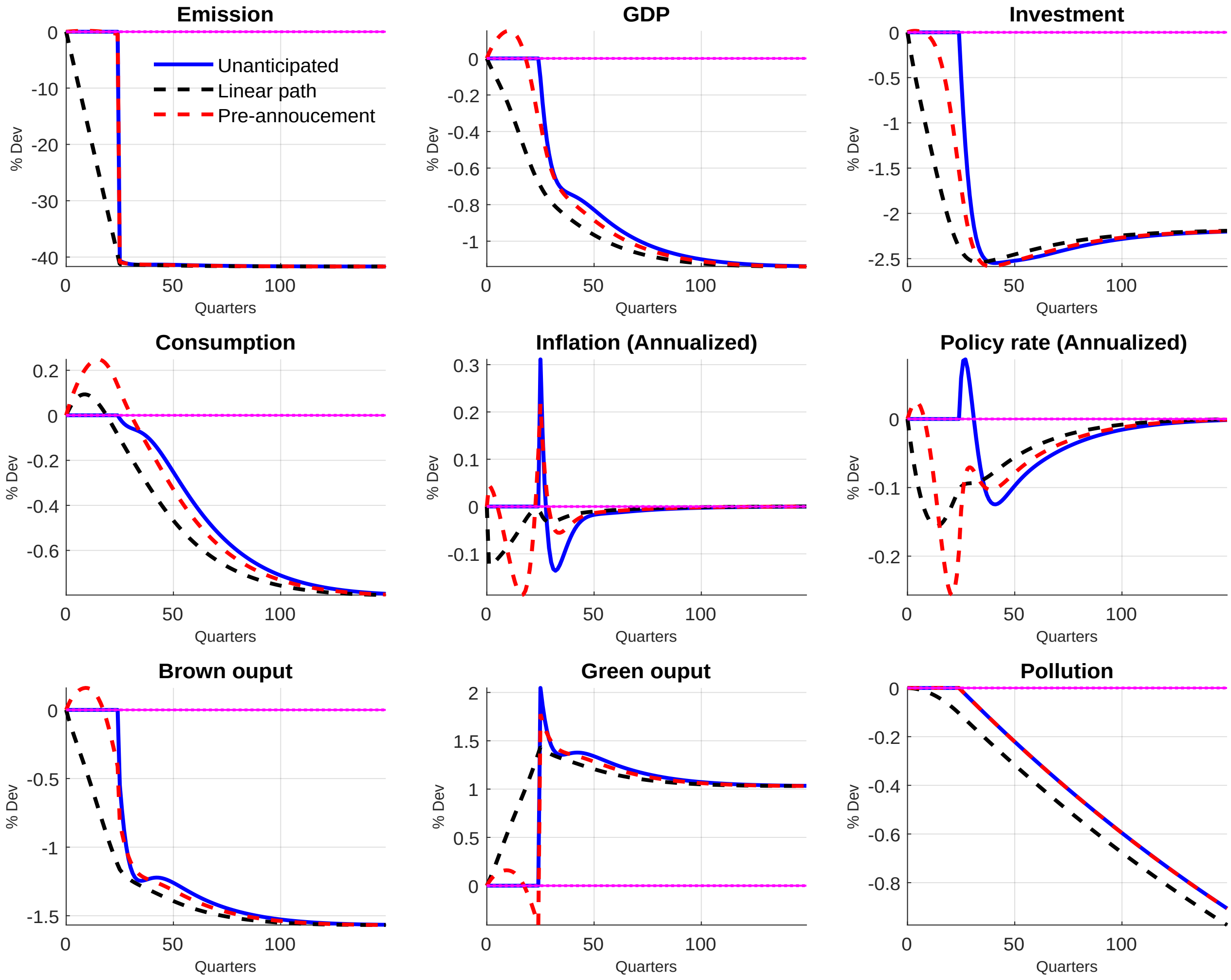

**Figure 8:** The impulse response of an unanticipated carbon price hike in the 25th period (blue), the linear increasing carbon price from period 0 (black) and preannouncement of carbon policy in period 0 that materialize in period 25 (red). The time is in quarters. Impulse responses are in percentage deviation from steady states.

# 5 Optimal Monetary and Green Credit Policy

In section 4, it is noticeable that financial frictions have a significant impact on the amplification of carbon prices in macroeconomics. Drawing from the experiences of the Global Financial Crisis (GFC), this highlights the importance of implementing macroprudential policies during the transition period. This part of the study focuses on determining the optimal policy response considering the transition risk.

The paper explores the concept of simple optimal monetary policy and demonstrates how macroprudential measures targeting green sectors can complement monetary policy during a forced transition. Additionally, the study proposes an approach to determine the optimal carbon tax policy. While a common approach aims to maximize welfare by reducing carbon taxes during both economic booms and downturns, this contradicts the goals set forth by the Paris Agreement and the recommendations of institutions such as the IMF and IEA. Instead, this study incorporates emissions within the objective function together with the welfare measurement, considering them on the same scale as the household utility. This enables the determination of an optimal carbon tax response. Another approach, inspired by Dück and Le (2023), involves utilizing a joint central bank loss function with the government to simultaneously determine optimal monetary and carbon prices. This integrated approach recognizes the interdependencies between these policy tools.

## 5.1 Optimal Macroprudential Policy

We compare the macro implications of two alternative policy regimes relative to the benchmark regime. The first alternative policy is an optimal Taylor rule, under which the reaction coefficients $\rho_r$, $\rho_\pi$ and $\rho_y$ in Equation 41 are chosen to maximize the representative household's welfare, while the required reserve is kept at the steady state value for both sectors (i.e., $\tau^i = 0.02$). The second alternative policy is a joint rule, under which all 5 reaction coefficients $\rho_r$, $\rho_\pi$, $\rho_y$, $\phi_G$ and $\phi_B$ are optimally set to maximize welfare. Our welfare is defined as the sum of current and future household utility flow. Welfare is computed as the stochastic mean of the welfare function $\mathcal{W}_t = U_t + \beta E_t\left(\mathcal{W}_{t+1}\right)$ at the second order with pruning where $U_t$ takes the form:

$$U_t = log(C_t - \kappa C_{t-1}) - \Psi \frac{H_t^{1+\varphi}}{1+\varphi} \tag{50}$$

We measure welfare gains under each counterfactual policy relative to the benchmark model as the percentage change. $\mathcal{W}_B$ is the welfare measurement of our benchmark calibration and

$\mathcal{W}$ is the maximized welfare given the policy rules.

$$\mathcal{W}_t = U_t + \beta E_t \left(\mathcal{W}_{t+1}\right) \tag{51}$$

$$\Delta E(\mathcal{W}) = 100 \times E\left(\frac{\mathcal{W} - \mathcal{W}_B}{\mathcal{W}_B}\right) \tag{52}$$

The welfare maximization is conducted subject to the Taylor rule and macroprudential rule. In this paper, I introduce the macroprudential rule to balance between our setting and the practice of the Basel III. Hence, the reserve requirement is a reaction function to the total credit[10].

$$\max_{\{\rho_r, \rho_\pi, \rho_y, \phi^G, \phi^B\}} \quad \mathcal{W}_t = U_t + \beta E_t \left(\mathcal{W}_{t+1}\right)$$

$$\begin{aligned} s.t. \quad \ln\left(\frac{R_t}{R_{ss}}\right) &= \rho_r ln\left(\frac{R_{t-1}}{R_{ss}}\right) + (1-\rho_r)\left(\rho_\pi ln\left(\frac{\pi_t}{\pi_{ss}}\right) + \rho_y ln\left(\frac{GDP_t}{GDP_{t-1}}\right)\right) \\ \tau_t^G &= \tau_{ss}^G + \phi^G ln\left(\frac{B_{G,t} + B_{B,t}}{B_G + B_B}\right) \\ \tau_t^B &= \tau_{ss}^B + \phi^B ln\left(\frac{B_{G,t} + B_{B,t}}{B_G + B_B}\right) \end{aligned}$$

| Parameters | Benchmark | Taylor rule | Macroprudential rule |
|---|---|---|---|
| $\rho_r$ | 0.93 | 0.8507 | 0.7581 |
| $\rho_\pi$ | 2.73 | 1.5926 | 1.4359 |
| $\rho_y$ | 0.1 | 0.3872 | 0.6011 |
| $\phi^G$ | 0 | 0 | 0.6903 |
| $\phi^B$ | 0 | 0 | -0.0000 |
| $\Delta E(\mathcal{W})$ | 0.00 | 0.0154 | 3.4663 |

First, the optimal Taylor rule parameter only generates a small welfare gain. In our setup, monetary policy cannot have an allocation effect between sectors. Therefore, it can only mitigate the impact on output and inflation. However, due to the ambitious carbon price hike, output decreases and "greenflation" is generated in the first few periods, resulting in a tradeoff in the central bank's mandate. Consequently, it is expected that relying solely on the optimal Taylor rule will only produce a limited welfare gain and the need for a tool

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[10] I also conducted different reaction functions objective, i.e. total capital. The results only change quantitatively and can be found in the Appendix.

with an allocation effect becomes pronounced.

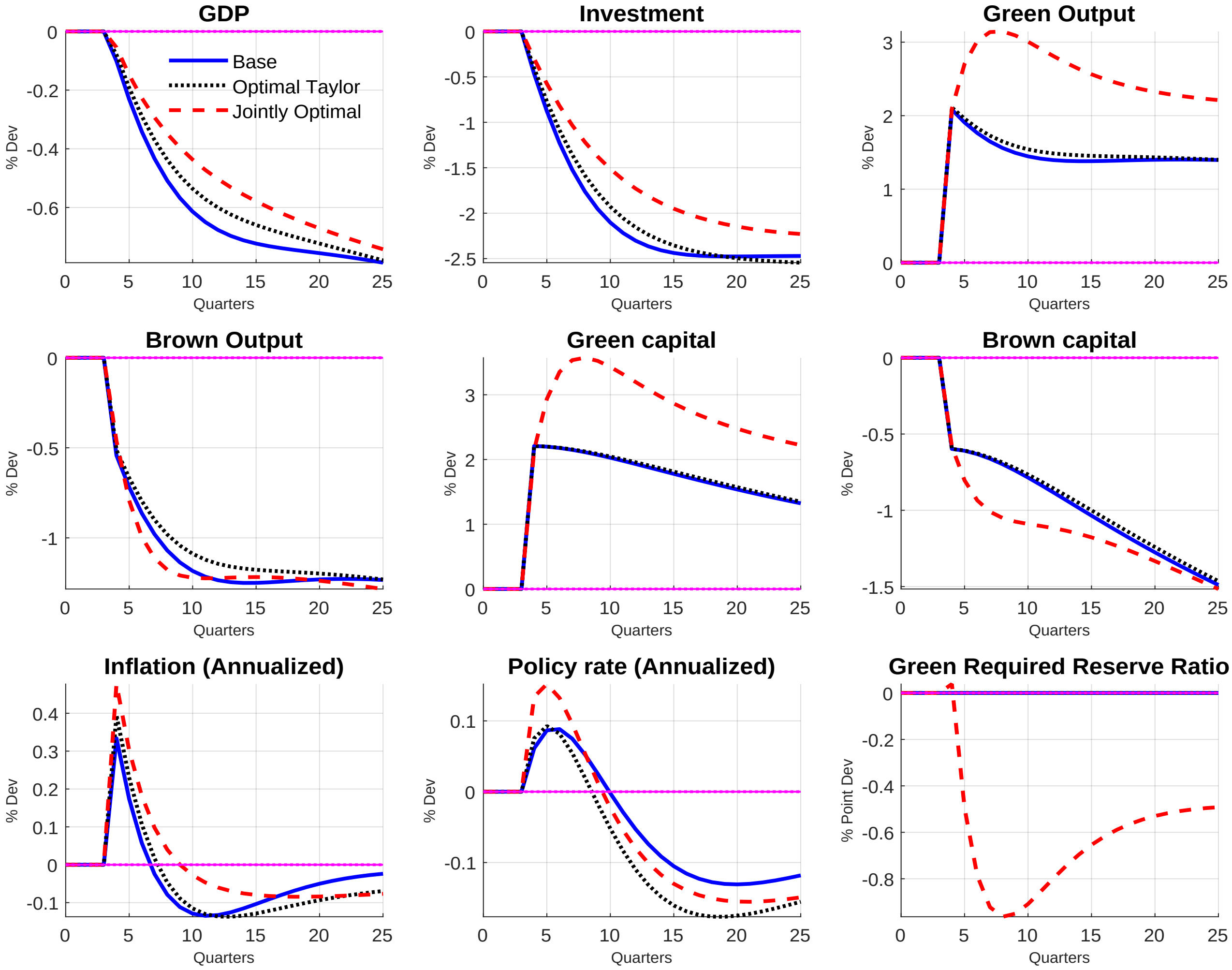

**Figure 9:** The impulse response of an unanticipated shock with optimal rules. Time is in quarters. Impulse responses are in percentage deviation from steady states if not specified otherwise. The blue line is the Base model. The dashed black line is the model with the optimal Taylor rule. The dashed red line is the model with the jointly optimal Taylor rule and reserve requirement.

Secondly, in the process of determining the joint optimal policies, it is evident that central banks can enhance their effectiveness in each sector by combining green macroprudential tools with monetary policy. Moreover, our analysis reveals significant welfare gains and a reduction in transition costs as more capital is allocated to the green sector. To ensure a realistic policy framework, I have imposed a lower bound that prevents the green macroprudential subsidy from falling below zero. Figure 19 illustrates the effectiveness of green macroprudential measures in mitigating the adverse effects of implementing a carbon price. These measures effectively dampen the response of key macroeconomic variables, thereby highlighting their crucial role in achieving sustainable outcomes.

The obtained results align with our expectations. Notably, the positive response of the green reserve requirement to the overall market credit plays a crucial role in directing more capital towards the green sectors. Consequently, this increased allocation of capital stimulates production within the green sector and mitigates the risks associated with carbon policies by facilitating the substitution of the green sector.

Furthermore, the analysis of the optimal welfare simple rule reveals a non-significant negative impact of the reserve requirement on the brown sectors[11]. This finding is intriguing since one might initially anticipate that raising the reserve requirement for borrowing in the brown sectors would also encourage capital flow towards the green sector. Nevertheless, due to the contractionary effects resulting from the carbon price hike, it becomes apparent that increasing the reserve requirement for brown loans can exacerbate the situation, failing to generate welfare gains.

## 5.2 Optimal Carbon Pricing

In this section, I analyze the optimal carbon pricing strategy under a positive total factor productivity (TFP) shock. Given the welfare-reducing nature of carbon pricing, the optimal carbon price, determined through a standard welfare maximization approach, appears to decrease during both boom and burst periods. However, with a positive TFP shock, we anticipate an increase in production, which in turn leads to higher emissions.

To ensure that the importance of emissions is properly accounted for in our analysis, I incorporate the stochastic mean response of emissions, adjusted to be the same scale of the household utility, alongside the approach proposed by Dück and Le (2023). We evaluate policies based on two welfare measurements in each scenario: $\mathcal{W}_t^{env}$, which includes emissions, and $\mathcal{W}_t$, which represents the standard welfare measurement. By comparing the outcomes in both welfare measurements, I aim to identify any differences and their implications. Last but not least, I also conduct the optimal Taylor rule parameters by considering the optimal reaction of the tax to emissions at the same time.

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[11] We observe a marginal negative value for the parameter $\phi^B$.

$$\mathcal{W}_t = U_t + \beta E_t \left( \mathcal{W}_{t+1} \right) \tag{53}$$

$$\mathcal{W}_t^{env} = \mathcal{W}_t - E_t(e_t) \tag{54}$$

$$\tau_t^e = \tau_{ss}^e + \phi^e (e_t - e_{ss}) \tag{55}$$

| Parameters | Benchmark | $\mathcal{W}_t$ | $\mathcal{W}_t^{env}$ |
|---|---|---|---|
| $\rho_r$ | 0.93 | 0.9011 | 0.9344 |
| $\rho_\pi$ | 2.74 | 2.9163 | 2.9214 |
| $\rho_y$ | 0.1 | 0.1012 | 0.0995 |
| $\phi_e$ | 0 | -0.0979 | 0.4859 |

As mentioned, when emissions are not explicitly considered, the optimal tax response may act as a subsidy depending on the magnitude of the shock, responding negatively to emissions. However, such an approach contradicts our collective efforts to combat climate change and reduce emissions.

This work proposes that the optimal tax should be designed to align with the goals of reducing emissions, even if it goes against the preferences of households as reflected in the standard welfare function. By internalizing the emission aspect and explicitly considering its impact, we can develop a tax policy that effectively addresses climate change concerns. It is crucial to recognize that the standard welfare function while capturing various dimensions of societal welfare, may not fully account for the negative externalities associated with emissions. Therefore, incorporating emission considerations into the design of the optimal tax becomes essential to achieve sustainable outcomes and effectively tackle climate change challenges.

# 6 Extension: Open Economy and Green Capital Inflow Control

Given the significant levels of trade openness and financial openness within the Euro Area, it is natural to inquire about the implications for foreign capital during the transition period.

In this section, I expand the scope of our analysis to include a standard small open economy framework. The calibration is designed to align with the trade-to-GDP ratio observed in the Euro Area. Importantly, I incorporate the possibility of capital inflows, similar to the approach taken by Liu et al. (2021*a*).

The changes in the model are minimal. The household can participate in the international financial market similar to the seminal work of Gali and Monacelli (2005). For simplicity, the pricing of the wholesale sector uses producer currency pricing and all the prices are set in domestic currency. Both green and brown sectors can access financing resources from foreign investors. Most importantly, we assume the foreign loans into intermediate firms. Hence, the total green and brown firm bonds turn into the following equations. Other additional equations can be found in the Appendix.

$$B_{G,t} = B^D_{G,t} + s_t B^F_{G,t} \tag{56}$$

$$B_{B,t} = B^D_{B,t} + s_t B^F_{B,t} \tag{57}$$

where the superscript D and F stands for domestic and foreign, respectively. Most importantly, the loan from abroad is subject to a risk premium:

$$\left(1 - \tau_t^{G,f}\right) r_{G,t} = r_t^* \Phi \left( \frac{B^F_{G,t}}{Y_t} \right) \tag{58}$$

$$\left(1 - \tau_t^{B,f}\right) r_{B,t} = r_t^* \Phi \left( \frac{B^F_{B,t}}{Y_t} \right) \tag{59}$$

In the calibration of the new parameters, I calibrate to match the trade balance to the GDP ratio of EA. The only element yet to be considered is the capital inflow tax in the steady state. For simplicity, I also calibrate the steady state of capital inflow tax to be 2% which is equal to the reserve requirement ratio. The extension aims to demonstrate a broader application of macroprudential policy without altering the key findings of the analysis within a closed economy. We can interpret the closed economy as our open economy in autarky. Later in this section, we will observe that the impulse response of the model only changes slightly in quantitative terms compared to our closed economy setup.

Intuitively, a decrease in $\tau_t^{G,f}$ will attract a greater inflow of capital into the green sector. This increases capital inflow and enhances green firms' access to foreign funding, resulting in higher levels of relative green output and overall productivity. However, the inflow of foreign capital reduces the domestic credit market, leading to a decrease in domestic loans and a reduced demand for deposits in the banking sector. This reduction in market lending rates necessitates a decrease in deposit rates to ensure the continued operation of banks (i.e., to prevent bank bankruptcies). The decline in deposit rates amplifies distortions in households' consumption-savings decisions, leading to a decrease in welfare. However, it also attracts foreign capital into the green sector, providing a mechanism to mitigate the effects of transition risk. This attraction of foreign capital operates in a similar manner as the green reserve requirement, offering support for addressing challenges during the transition to a greener economy. Hence, I impose a positive reaction to capital inflows in the following equation and optimize the Taylor rule parameters accordingly.

$$\tau_t^{G,f} = \tau_{ss}^{G,f} + \phi_{G,f} \log(\frac{B_{G,t}^D + B_{B,t}^D}{B_G^D + B_B^D}) \tag{60}$$

$$\tau_t^{B,f} = \tau_{ss}^{B,f} + \phi_{B,f} \log(\frac{B_{G,t}^D + B_{B,t}^D}{B_G^D + B_B^D}) \tag{61}$$

In line with the green macroprudential policy, I allow for its responsiveness to the total domestic credit within the economy. To maintain analytical tractability, I focus solely on the optimal capital flow and Taylor rule parameters. The analysis aims to demonstrate the benefits of domestic capital regulation, as presented in Section 5.1. Again, welfare is computed as the stochastic mean of the welfare function $\mathcal{W}_t = U_t + \beta E_t(\mathcal{W}_{t+1})$ at the second order with pruning. We measure welfare gains under each counterfactual policy relative to the benchmark model as the percentage change. $\mathcal{W}_B$ is the welfare measurement of our benchmark calibration.

$$\mathcal{W}_t = U_t + \beta E_t(\mathcal{W}_{t+1}) \tag{62}$$

$$\Delta E(\mathcal{W}) = 100 \times E\left(\frac{\mathcal{W} - \mathcal{W}_B}{\mathcal{W}_B}\right) \tag{63}$$

| Parameters | Benchmark | Taylor rule | Capital Control |
|---|---|---|---|
| $\rho_r$ | 0.93 | 0.0777 | 0.2411 |
| $\rho_\pi$ | 2.73 | 1.5837 | 1.5159 |
| $\rho_y$ | 0.1 | 0.1758 | 0.1005 |
| $\phi_{G,f}$ | 0 | 0 | 0.1005 |
| $\phi_{B,f}$ | 0 | 0 | -0.0000 |
| $\Delta E(\mathcal{W})$ | 0.00 | 0.3008 | 0.1097 |

Similar to the optimal macroprudential exercise, I also impose a lower bound of zero on the decrease in the capital inflow tax, thereby restricting it from acting as a subsidy. The impulse response function (IRF) of the green capital control policy can be interpreted as a 0.1% decrease at its peak from an initial 2% capital inflow tax.

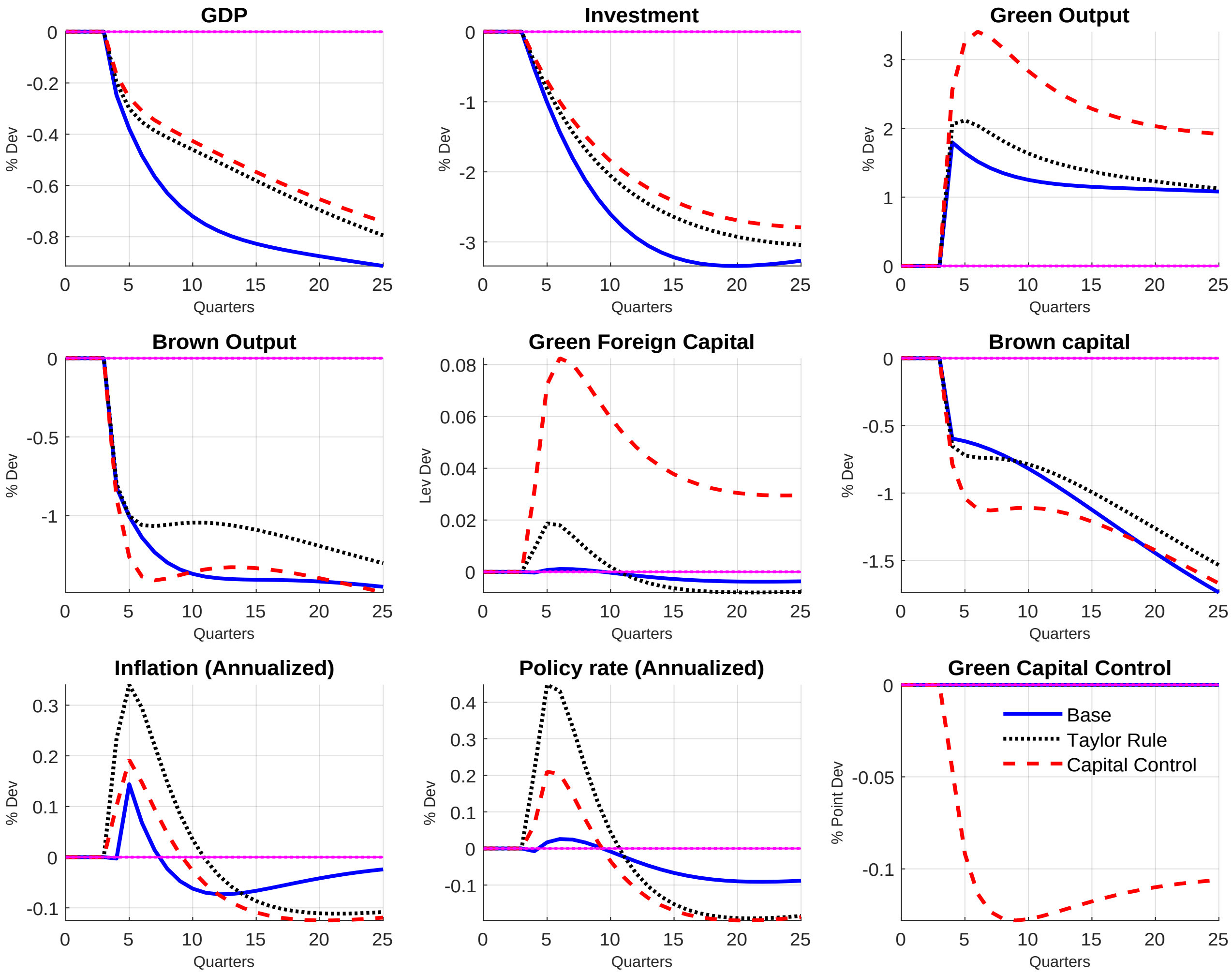

**Figure 10:** Unanticipated shock with optimal rules with and without green capital control. Time is in quarters. Impulse responses are in percentage deviation from the steady state if not specified otherwise. The blue line is the Base model. The dashed black line is the model with the optimal Taylor rule. The dashed red line is the model with the jointly optimal Taylor rule and CFMs.

The results obtained from the optimal policies exercise partially support our initial conjecture. The welfare gain achieved through the optimal policy with capital inflow control is found to be smaller compared to implementing only the optimal Taylor rule. This finding is consistent with the findings documented in Liu et al. (2021*b*), where capital inflow subsidies only lead to welfare gains under specific financial stress conditions. In my results, although there are still some minor welfare gains compared to the benchmark, they are smaller compared to the cases of the optimal Taylor rule or macroprudential rule. This creates a distortion in the consumption-saving problem, which limits the potential welfare gains.

Figure 10 illustrates the impact of an unanticipated carbon price using the optimal parameters derived from the welfare maximization exercise. The results clearly show that the implementation of the optimal capital control policy leads to a significant increase in green production while simultaneously dampening brown production. In our model, we do not endogenously model foreign investors, which means that they do not anticipate the burden of the carbon price in the brown sector. As a result, there is a capital reallocation from the brown sector to the green sector.

The findings highlight the crucial role played by the management of foreign capital flows in mitigating the macroeconomic environment, particularly in terms of output. We observe a smaller coefficient in response to output in the Taylor rule with the inclusion of the optimal capital inflow tax, given a similar decline in output in both cases.

# 7 Conclusion

This paper studies the macro-financial implications of using carbon prices to achieve ambitious greenhouse gas (GHG) emission reduction targets. My empirical evidence shows a 0.7% output loss and a rise of 0.3% in inflation in response to a one standard deviation shock on carbon policy. I also observe financial instability and allocation effects between the clean and highly polluted energy sectors. Using a medium-large macro-financial DSGE model with environmental aspects, I show the recessionary effect of an ambitious carbon price implementation to achieve climate targets, a 40% emission reduction causes a 0.7%

output loss, and a zero-emission economy in 30 years causes a 2.7% output loss. I document an amplified effect of the banking sector during the transition path. The paper also uncovers the beneficial role of pre-announcements of carbon policies in mitigating inflation volatility by 0.2% at its peak, and our results suggest well-communicated carbon policies

Furthermore, the paper explores the crucial role of the financial sector in amplifying the effects of ambitious carbon policies. To facilitate the transition to a greener economy, the proposed approach involves the use of heterogeneous reserve requirements, taking into account the heterogeneity between green and brown banks. The study also examines the impact of green domestic policies and capital inflow tax (subsidy), revealing that while both measures can mitigate the effects of carbon policies, the latter may result in less welfare gain due to distortions in consumption-saving decisions. Overall, the analysis demonstrates that macroprudential tools in both domestic and international credit play a complementary role in monetary policy in the transition to a greener economy.

Although this paper uses the EA data for empirical analysis and a calibrated model for EA, I believe the policy implication is highly relevant for other countries especially emerging and developing countries where capital flow management is highly active. Using the example of EA, the paper can be used by other authorities around the world to develop their carbon policy and use a joint set of policies to assist the transition of their economy to a green economy. Lastly, the framework can be easily applied to study physical risk (i.e. climate, weather shock). This is interesting for future research.

# Appendix

## A The Role of Green Sectors

In this section, I investigate the sensitivity of the share of the green sector in response to transition risk. As carbon pricing only affects the brown sector and creates allocation effects, it is natural to think that the economy with a bigger share of the green industry can suffer from less severe transition risk. Moreover, it is highly interesting to think about the elasticity of substitution between green and brown goods. Hence, I show the variation of our results in terms of the share and elasticity of substitution between the green and brown sectors as discussed in Section 4.3.2.

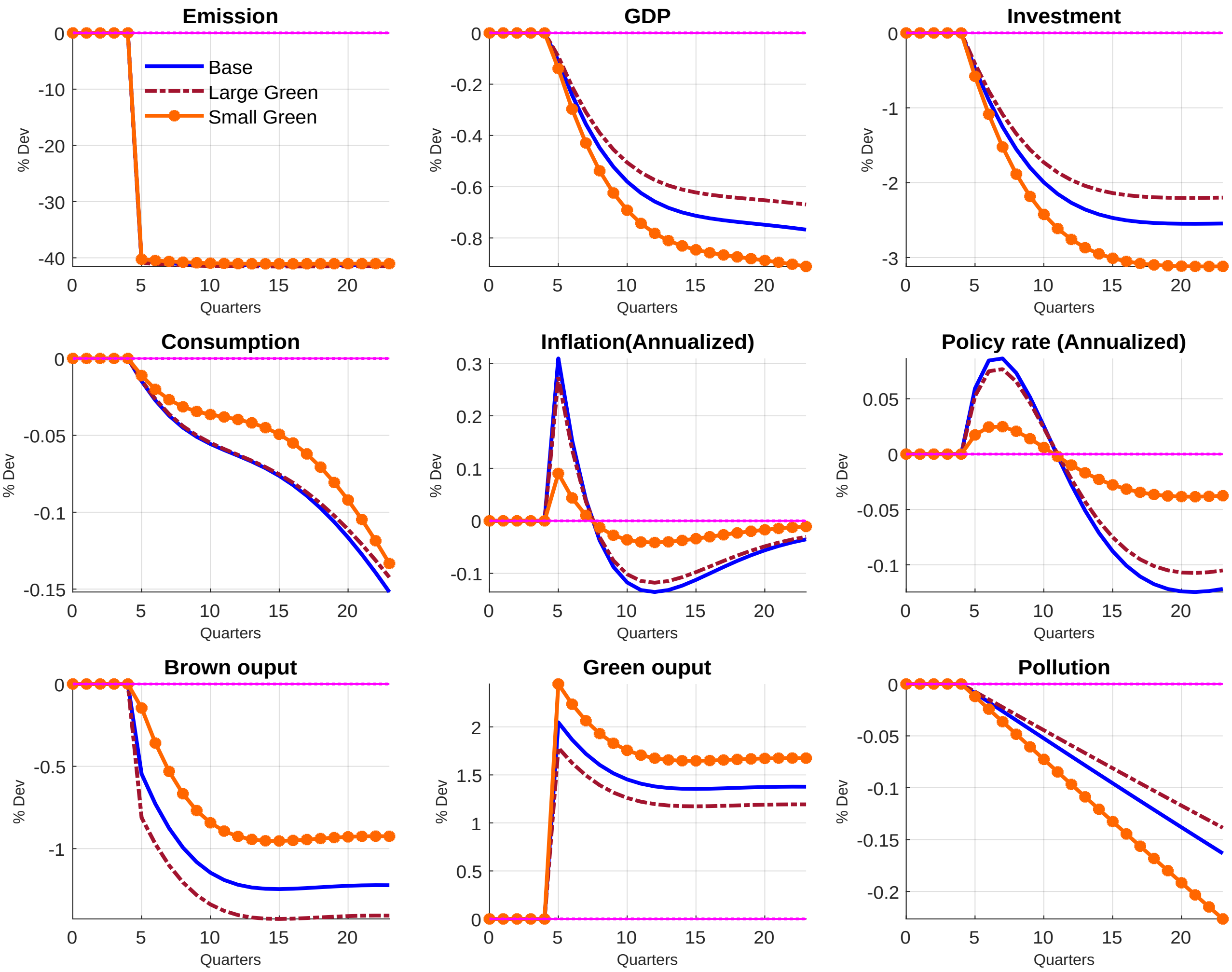

**Figure 11:** Unanticipated shock after 5 periods. Time is in quarters. Impulse responses are in percentage deviation from steady states. The blue line is our Base model. The red dashed line is the model with a larger share of green goods. The orange line is the model with a smaller share of green goods

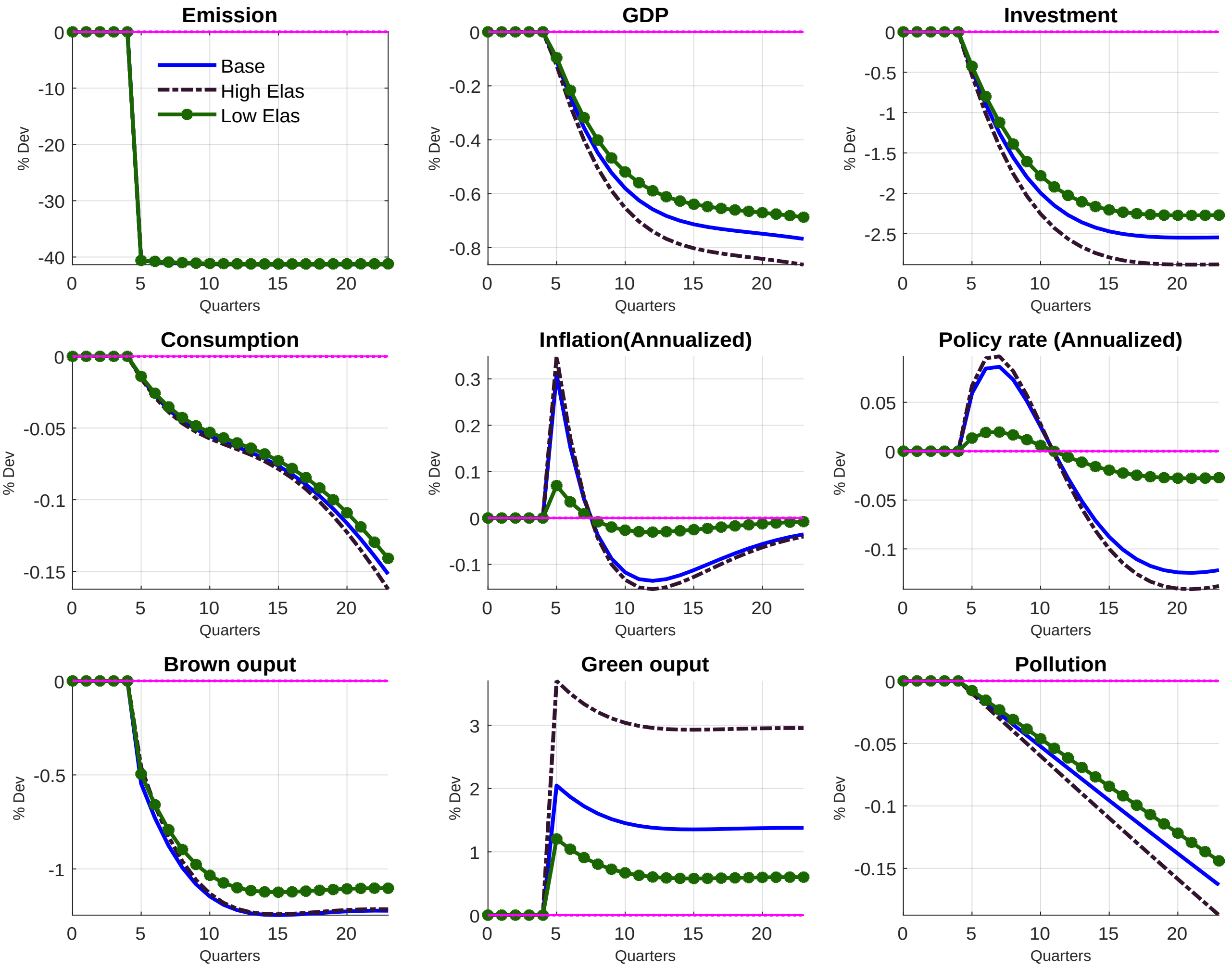

**Figure 12:** Unanticipated shock after 5 periods. Time is in quarters. Impulse responses are in percentage deviation from steady states. The blue line is our Base model. The black dashed line is the model with high elasticity of substitution. The dark green line is the model with low elasticity of substitution

# B Robustness Check

In this section, I show that the main results of the empirical analysis hold for standard local projection and Bayesian VAR. For both methods, I use the surprise carbon policy series as the instrument variable. I also include the international related variables on capital account and real effective exchange rate.

First, I vary the lag from 6 to 12 and find that our empirical evidence holds.

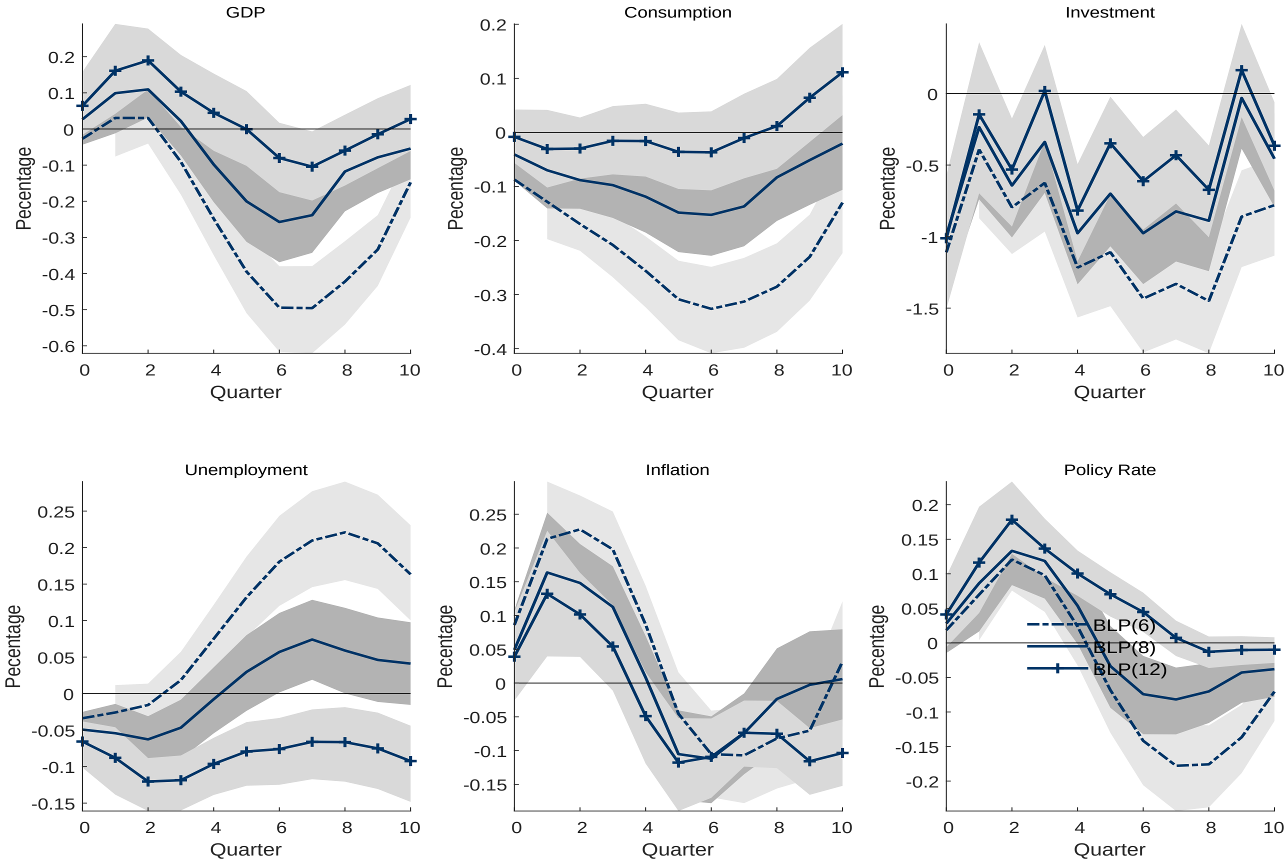

**Figure 13:** The impulse response of a 1 standard deviation carbon policy shock using BLP with 6, 8 and 12 lags. The grey shade shows a 68% credible set of our estimation.

It is natural to see that our analysis was conducted during the time that the ECB set the zero lower bound on their policy rate. Hence, I replace the policy rate with the shadow rate by Wu and Xia (2016). We see that the results hold for the using the shadow rate also.

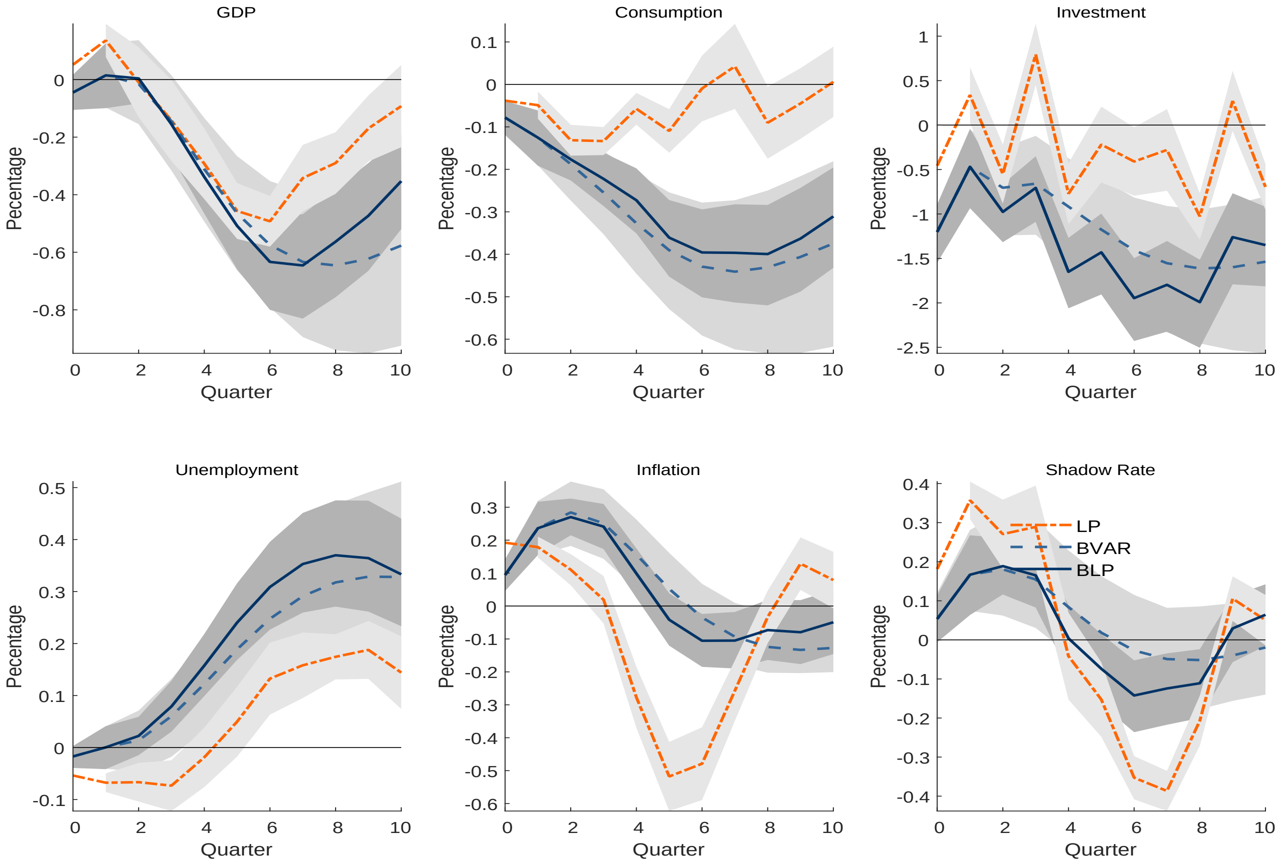

**Figure 14:** The impulse response of a 1 standard deviation carbon policy shock using BLP, LP, BVAR using shadow rate. The grey shade shows a 68% credible set of our estimation.

# C Data Summary

| Variables | Descriptions | Source |
|---|---|---|
| $GDP_t$ | Real GDP | Eurostat |
| $C_t$ | Real Consumption (Private final consumption expenditure) | Eurostat |
| $I_t$ | Real Investment (Gross fixed capital formation) | Eurostat |
| $EMP_t$ | Unemployment Rate (Harmonised) | Eurostat |
| $\pi_t$ | Inflation rate (Harmonised Consumer Price Index) | Eurostat |
| $R_t$ | Policy rate, EURIBOR 3M | Eurostat |
| $CA_t$ | Capital Account Balance | Eurostat |
| $STOXX600_t$ | Stock Index STOXX600 | Reuter |
| $KOL_t$ | VanEck Vectors Coal ETF | Reuter |
| $ICLN_t$ | Shares Clean Energy ETF | Reuter |
| $XLE_t$ | Energy Select Sector SPDR Fund | Reuter |
| $SPR_t$ | Credit Spread (ICE BofA) | FRED |
| $E_t$ | Emission, (Yearly, using interpolation) | The World Bank |
| $FS_t$ | Financial Stress | Monin (2019) |
| $REER_t$ | Real Effective Exchange Rate | BIS |
| $Shadow_t$ | Shadow rate | Wu and Xia (2020) |

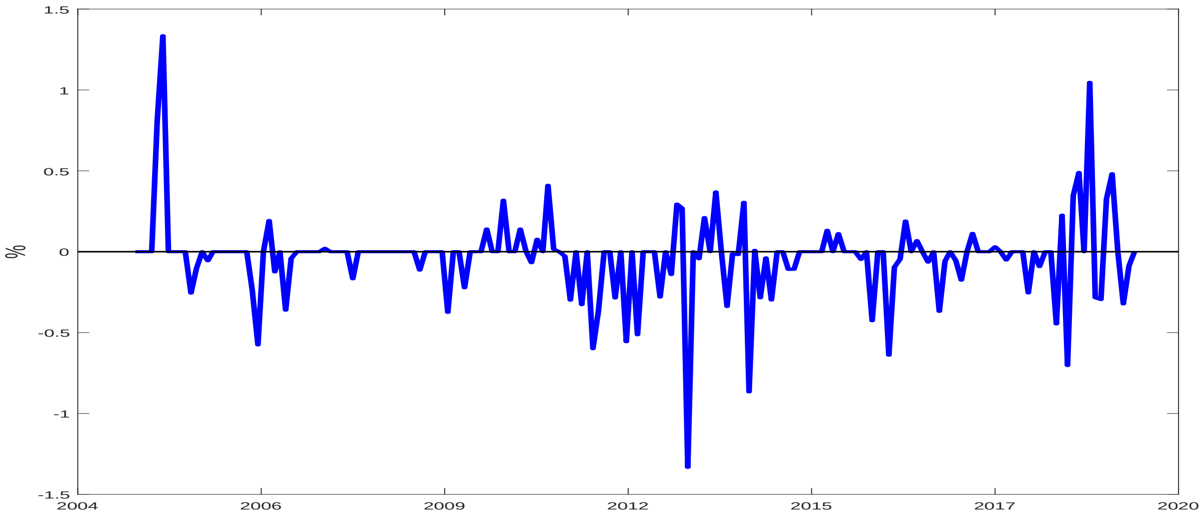

**Figure 15:** The high-frequency carbon policy surprises of Känzig (2023). The price change around regulatory events is defined as percentage changes at a daily frequency.

# D Other IRFs

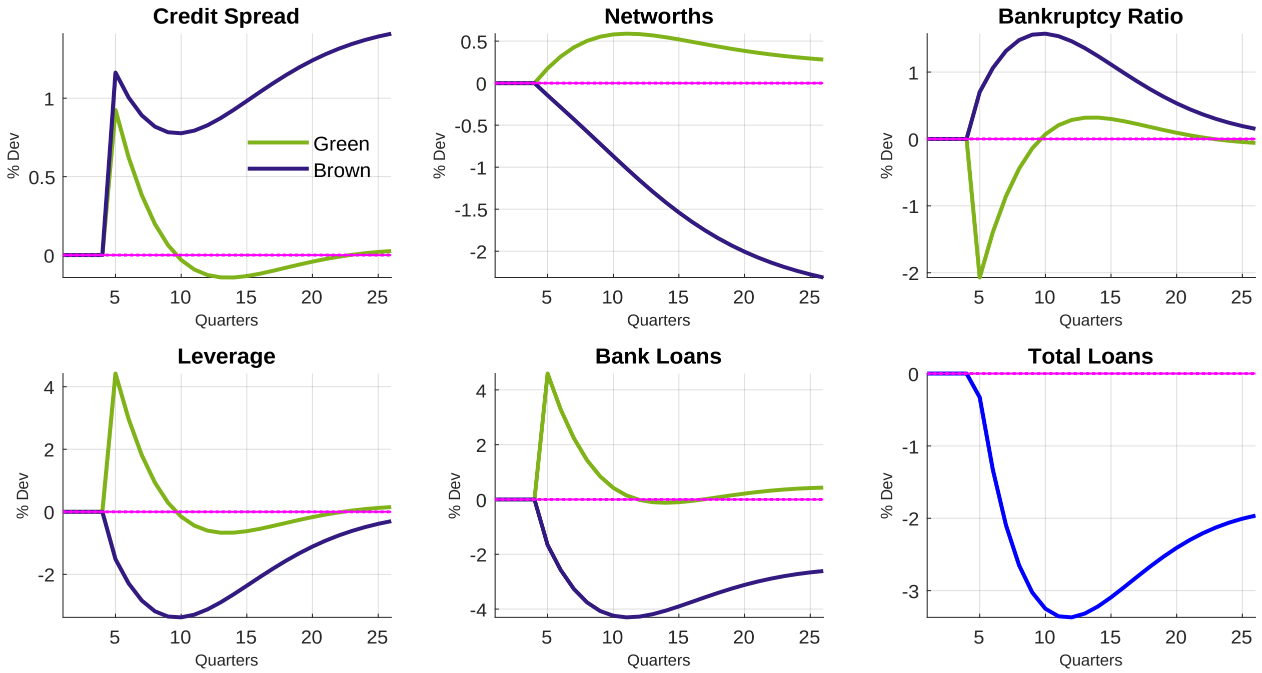

**Figure 16:** The impulse response of an unanticipated shock after 5 periods of the Base model. Time is in quarters. Impulse responses are in percentage deviation from steady states. The dark purple line is brown variables. The green line is green variables.

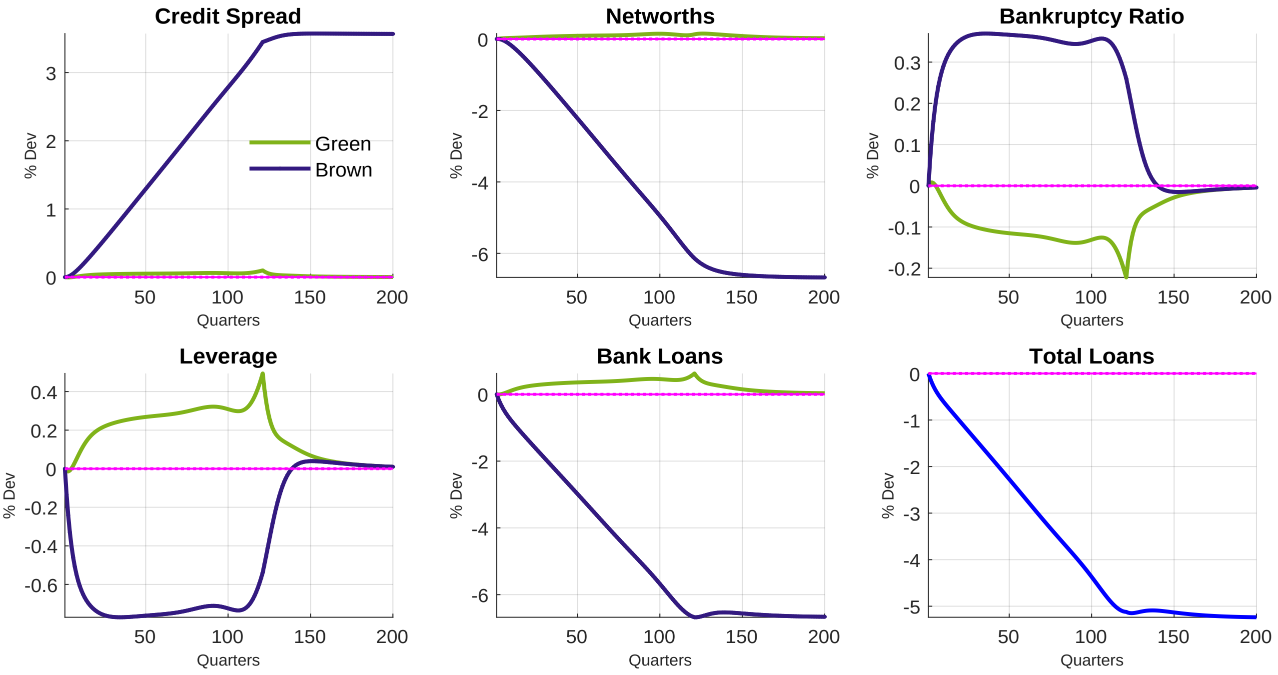

**Figure 17:** The impulse response of a linearly increasing carbon price to archive zero-emission after 30 years of the Base model. Time is in quarters. Impulse responses are in percentage deviation from steady states. The dark purple line is brown variables. The green line is green variables.

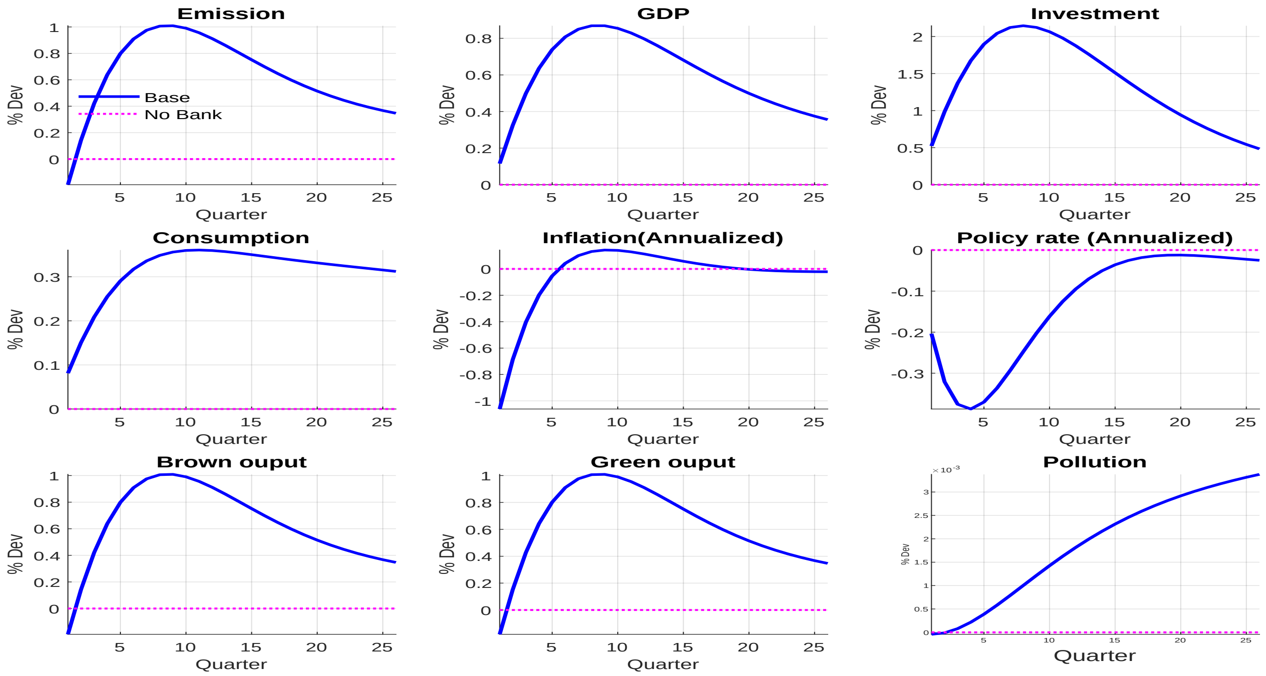

**Figure 18:** The impulse response of a positive TFP shock. Time is in quarters. Impulse responses are in percentage deviation from steady states.

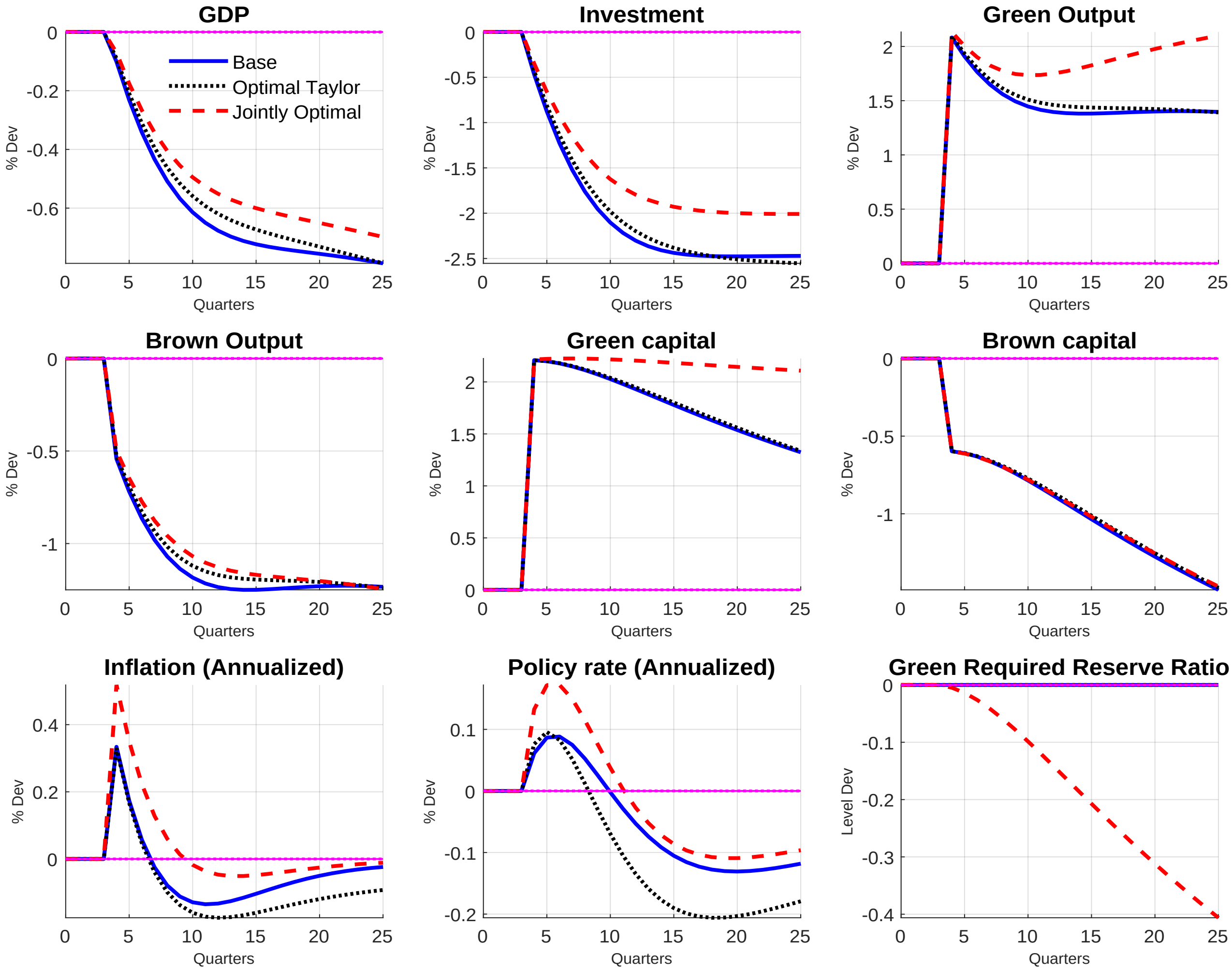

**Figure 19:** The impulse response of an unanticipated shock where the reserve requirement reacts to total capital. Time is in quarters. Impulse responses are in percentage deviation from steady states if not specified otherwise. The blue line is the Base model. The dashed black line is the model with the optimal Taylor rule. The dashed red line is the model with the jointly optimal Taylor rule and reserve requirement.

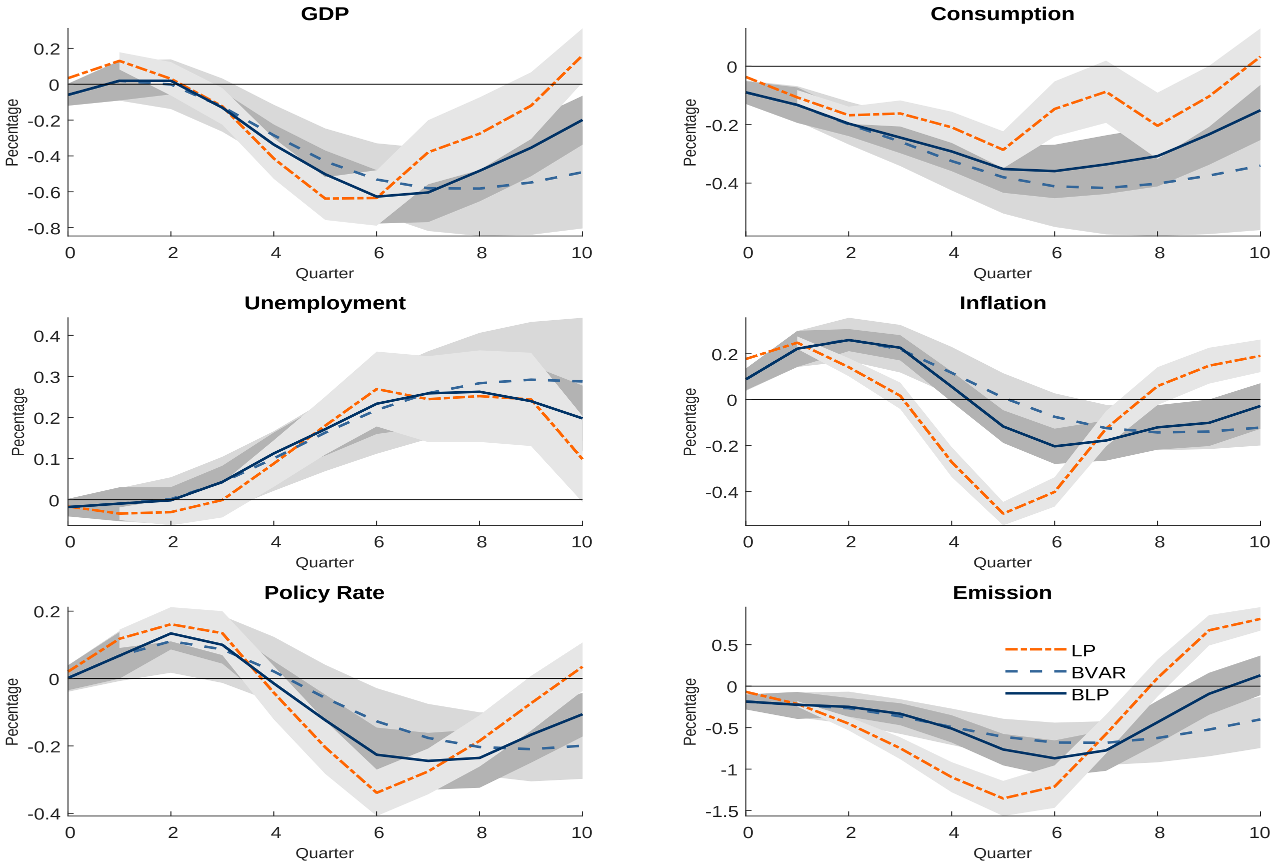

**Figure 20:** The impulse response of a 1 standard deviation carbon policy shock using BLP, LP, BVAR. The grey shade shows a 68% credible set of our estimation.

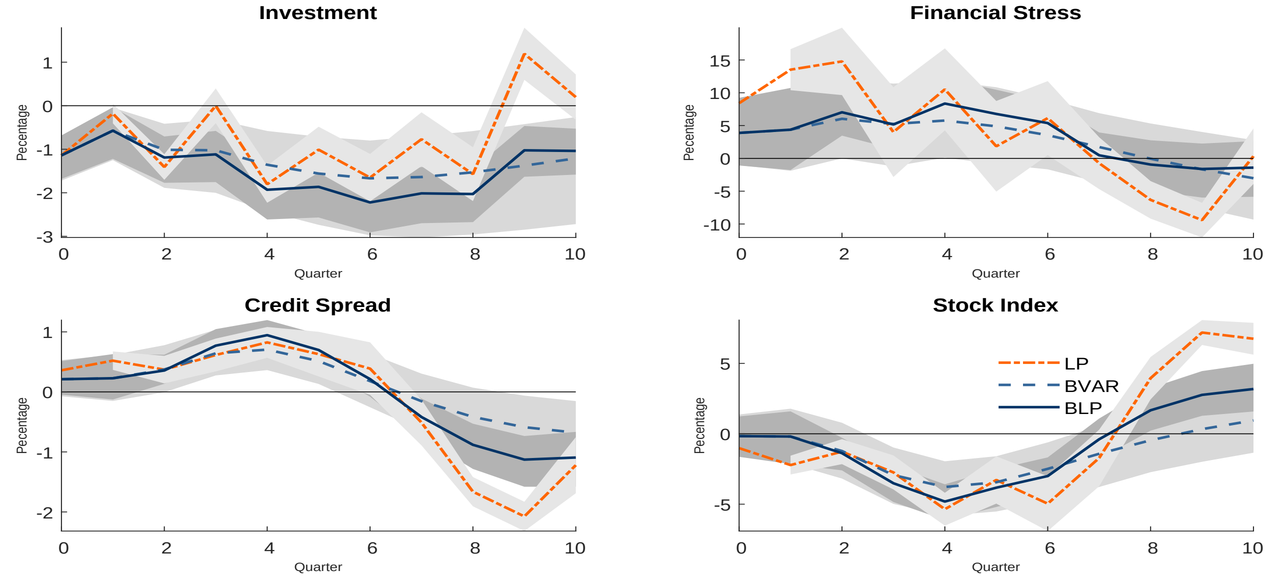

**Figure 21:** The impulse response of a 1 standard deviation carbon policy shock using BLP, LP, BVAR. The grey shade shows a 68% credible set of our estimation.

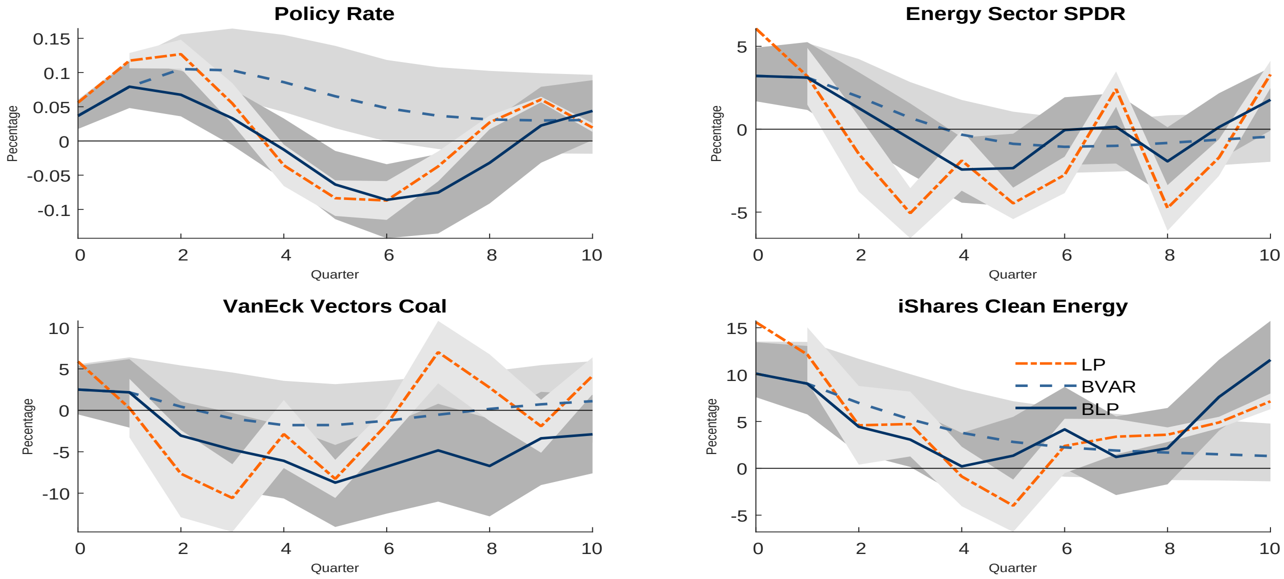

**Figure 22:** The impulse response of a 1 standard deviation carbon policy shock using BLP, LP, BVAR. The grey shade shows a 68% credible set of our estimation.

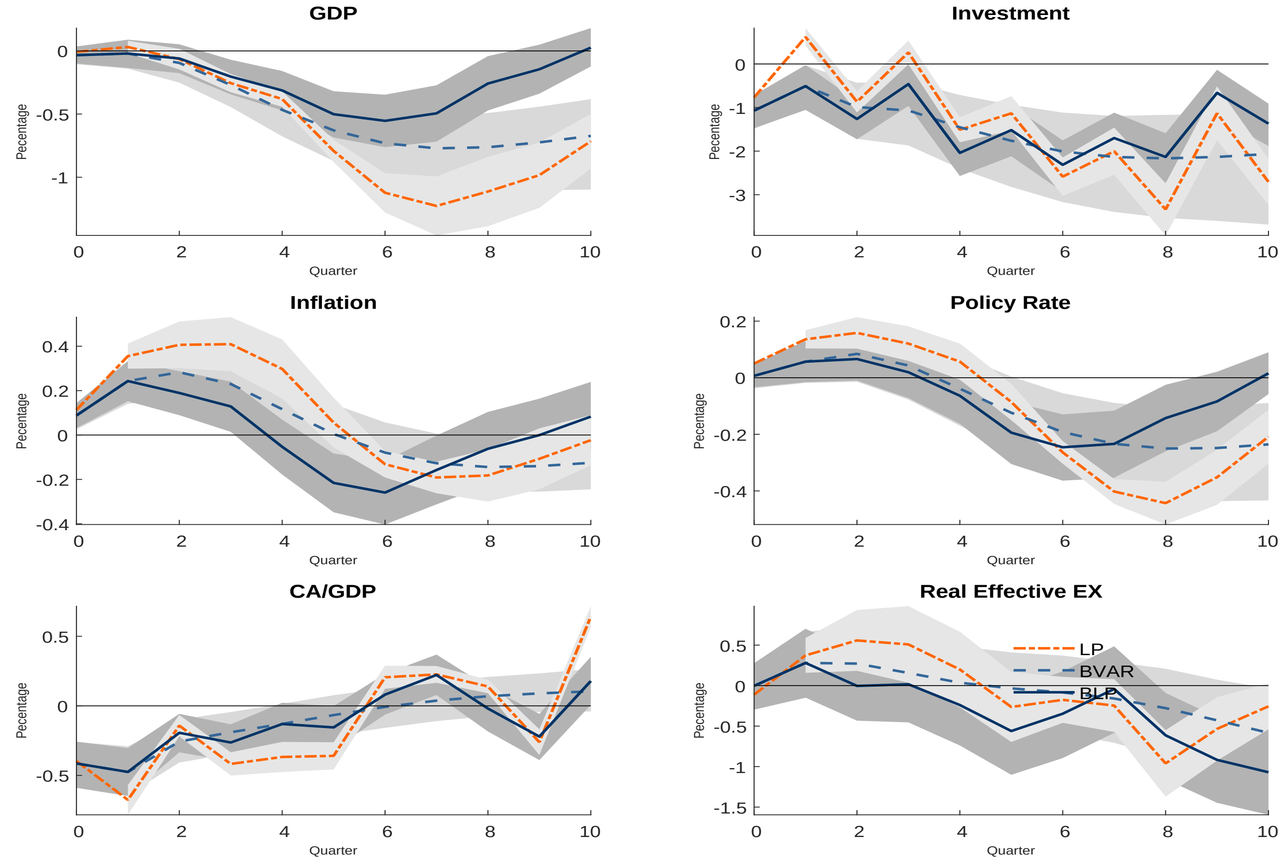

**Figure 23:** The impulse response of a 1 standard deviation carbon policy shock using BLP, LP, BVAR. The grey shade shows a 68% credible set of our estimation.

## E Model Derivations

### Household

$$\lambda_t = \frac{1}{C_t - \kappa C_{t-1}} - \beta \frac{\kappa}{C_{t+1} - \kappa C_t} \tag{64}$$

$$\lambda_t = \beta E_t \left( \lambda_{t+1} \frac{r_t}{\pi_{t+1}} \right) \tag{65}$$

$$w_t = \Psi \frac{H_t^{\varphi}}{\lambda_t} \tag{66}$$

$$q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} [(1-\delta) q_{t+1} + r_{t+1}^k] \tag{67}$$

$$1 = q_t \left[ 1 - \frac{\Omega_k}{2} \left( \frac{I_t}{I_{t-1}} - 1 \right)^2 - \Omega_k \frac{I_t}{I_{t-1}} \left( \frac{I_t}{I_{t-1}} - 1 \right) \right] + \beta E_t \left[ q_{t+1} \frac{\lambda_{t+1}}{\lambda_t} \Omega_k \left( \frac{I_{t+1}}{I_t} \right)^2 \left( \frac{I_{t+1}}{I_t} - 1 \right) \right] \tag{68}$$

### Production sector

$$\Gamma_t = (\phi Y_{G,t}^{\frac{\sigma-1}{\sigma}} + (1-\phi) Y_{B,t}^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}} \tag{69}$$

$$Y_{G,t} = \phi^{\sigma} \left( \frac{p_{G,t}}{p_{wc,t}} \right)^{-\sigma} \Gamma_t \tag{70}$$

$$Y_{B,t} = (1-\phi)^{\sigma} \left( \frac{p_{B,t}}{p_{wc,t}} \right)^{-\sigma} \Gamma_t \tag{71}$$

$$p_{wc,t} = (\phi^{\sigma} p_{G,t}^{1-\sigma} + (1-\phi)^{\sigma} p_{B,t}^{1-\sigma})^{\frac{1}{1-\sigma}} \tag{72}$$

$$Y_{it} = A_{it}^{env} \omega_{it} K_{it}^{1-\alpha} [(H_{it}^{e})^{1-\theta} (H_{it})^{\theta}]^{\alpha}, \tag{73}$$

$$A_t^{env} \ = \ \left(1 - \left(d_0 + d_1 \ X_t + d_2 \ X_t^2\right)\right) A_t \tag{74}$$

$$\log(A_t) \ = \ (1-\rho_a) \ \log(A) + \rho_a \ \log(A_{t-1}) + \epsilon_t^A \tag{75}$$

$$X_t \ = \ \eta \ X_{t-1} + e_t + e_t^{row} \tag{76}$$

$$e_t \ = \ \gamma_1 \ (1-\mu_t) \ Y_{B,t} \tag{77}$$

$$z_t \ = \ \theta_1 \ \mu_t^{\theta_2} \ Y_{B,t} \tag{78}$$

$$N_{G,t-1} + B_{G,t} = w_t H_{G,t} + w_{G,t}^e H_{G,t}^e + r_t^k K_{G,t} \tag{79}$$

$$\bar{\omega}_{G,t} = \frac{Z_{G,t} B_{G,t}}{\tilde{A}_{G,t}(N_{G,t-1} + B_{G,t})} \tag{80}$$

$$\tilde{A}_{G,t} = p_{G,t} A_{G,t} \left(\frac{1-\alpha}{r_t^k}\right)^{1-\alpha} \left[\left(\frac{\alpha(1-\theta)}{w_{G,t}^e}\right)^{1-\theta} \left(\frac{\alpha\theta}{w_t}\right)^{\theta}\right]^{\alpha} \tag{81}$$

$$\tilde{A}_{G,t}(N_{G,t-1} + B_{G,t}) g(\bar{\omega}_{G,t}) \geq r_{G,t} B_{G,t} \tag{82}$$

$$\frac{N_{G,t-1}}{N_{G,t-1} + B_{G,t}} = -\frac{g'(\bar{\omega}_{G,t})}{f'(\bar{\omega}_{G,t})} \frac{\tilde{A}_{G,t} f(\bar{\omega}_{G,t})}{r_{G,t}} \tag{83}$$

$$N_{G,t} = w^e_{G,t} H^e_{G,t} + \delta_G \tilde{A}_{G,t} (N_{G,t-1} + B_{Gt}) f(\bar{\omega}_{Gt}) \tag{84}$$

$$N_{B,t-1} + B_{B,t} = w_t H_{B,t} + w^e_{B,t} H^e_{B,t} + r^k_t K_{B,t} + \theta_1 \mu_t^{\theta_2} Y_{B,t} + \tau^e_t \underbrace{(1-\mu_t)\gamma_1 Y_{B,t}}_{e_t} \tag{85}$$

$$cost^E_t = \frac{\theta_1 (\mu_t)^{\theta_2} y^B_t + \tau^e_t (1-\mu_t)\gamma_1 y^B_t}{\tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})} \tag{86}$$

$$\bar{\omega}_{B,t} = \frac{Z_{B,t} B_{B,t}}{\tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})(1 - cost^E_t)} \tag{87}$$

$$\tilde{A}_{B,t}(N_{B,t-1} + B_{B,t})(1 - cost^E_t) g(\bar{\omega}_{B,t}) \geq r_{B,t} B_{B,t} \tag{88}$$

$$\frac{N_{B,t-1}}{(N_{B,t-1} + B_{B,t})(1 - cost^E_t)} = -\frac{g'_{B,t}(\bar{\omega}_{B,t})}{f'(\bar{\omega}_{B,t})} \frac{\tilde{A}_{B,t} f(\bar{\omega}_{B,t})}{r_{B,t}} \tag{89}$$

$$N_{B,t} = w^e_{B,t} H^e_{B,t} + \delta_B \tilde{A}_{Bt} (N_{B,t-1} + B_{B,t})(1 - cost^E_t) f(\bar{\omega}_{B,t}) \tag{90}$$

**Market Clearing**

$$\ln\left(\frac{R_t}{R_{ss}}\right) = \rho_r ln\left(\frac{R_{t-1}}{R_{ss}}\right) + (1-\rho_r)\left(\rho_\pi ln\left(\frac{\pi_t}{\pi_{ss}}\right) + \rho_y ln\left(\frac{GDP_t}{GDP_{t-1}}\right)\right) \tag{91}$$

$$\tau^G_t = \tau^G_{ss} + \phi^G ln\left(\frac{B_{G,t} + B_{B,t}}{B_{G,ss} + B_{B,ss}}\right) \tag{92}$$

$$\tau^B_t = \tau^B_{ss} + \phi^B ln\left(\frac{B_{G,t} + B_{B,t}}{B_{G,ss} + B_{B,ss}}\right) \tag{93}$$

$$Y_t = C_t + I_t + G_t + \theta_1(\mu_t^{\theta_2})y_{B,t} + \frac{\kappa_P}{2}(\pi_t - \bar{\pi})^2 Y_t + \tilde{A}_{G,t}(\frac{n_{G,t-1}}{\pi_t} + b_{G,t})m_g \int_0^{\omega_{\bar{G},t}} \omega \, dF(\omega)$$
$$+ \tilde{A}_{B,t}(\frac{n_{B,t-1}}{\pi_t} + b_{B,t})(1 - cost_t^E)m_b \int_0^{\omega_{\bar{B},t}} \omega \, dF(\omega) \tag{94}$$

$$K_{t-1} = K_{G,t} + K_{B,t}, \tag{95}$$

$$H_t = H_{G,t} + H_{B,t} \tag{96}$$

$$\frac{B_{G,t}}{(1 - \tau_t^G)} = D_t^G \tag{97}$$

$$\frac{B_{B,t}}{(1 - \tau_t^B)} = D_t^B \tag{98}$$

$$GDP_t = C_t + I_t + G_t \tag{99}$$

**Open Economy**

$$1 = \beta E_t \left( \frac{\lambda_{t+1}}{\lambda_t} r_t^* \frac{s_{t+1}}{s_t} \right) - \kappa_{b^*} \left( b_t^* - \bar{b^*} \right) \tag{100}$$

$$p_{wc,t} = pH_t \left( \frac{\epsilon - 1}{\epsilon} \right) + \Omega_P \left( \frac{\pi_{Ht} - \bar{\pi}}{\epsilon} \right) \pi_{Ht} - \beta E_t \left( \frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1}(\pi_{H,t+1} - \bar{\pi}) \frac{pH_{t+1}Y_{t+1}}{pH_t Y_t} \right) \tag{101}$$

$$\pi_{H,t} = \frac{p_{Ht}}{p_{Ht-1}} \pi_t \tag{102}$$

$$1 = (1-\gamma)\left(p_{Ht}\right)^{1-\eta} + \gamma\left(s_t\right)^{1-\eta} \tag{103}$$

$$\begin{aligned} Y_t = (1-\gamma)\left(p_{H,t}\right)^{1-\eta}\left(C_t + I_t\right) + \gamma^*\left(\frac{p_{H,t}}{s_t}\right)^{\eta} y_t^* + G_t + \theta_1(\mu_t^{\theta_2}) y_{B,t} + \frac{\kappa_P}{2}(\pi_t - \bar{\pi})^2 Y_t \\ + \tilde{A}_{G,t}\left(\frac{n_{G,t-1}}{\pi_t} + b_{G,t}\right) m_g \int_0^{\omega_{\bar{G},t}} \omega \, dF(\omega) \\ + \tilde{A}_{B,t}\left(\frac{n_{B,t-1}}{\pi_t} + b_{B,t}\right)(1 - cost_t^E) m_b \int_0^{\omega_{\bar{B},t}} \omega \, dF(\omega) \end{aligned} \tag{104}$$

$$B_{G,t} = B_{G,t}^D + s_t B_{G,t}^F \tag{105}$$

$$B_{B,t} = B_{B,t}^D + s_t B_{B,t}^F \tag{106}$$

$$TB_t = s_t bF_t - s_t R_{z,t-1}\frac{bF_{t-1}}{\pi_t^*} + r_t^* \Phi\left(\frac{B_{Gt}^F}{Y_t}\right) B_{G,t-1}^F s_t - B_{G,t}^F s_t + r_t^* \Phi\left(\frac{B_{Bt}^F}{Y_t}\right) B_{B,t-1}^F s_t - B_{B,t}^F s_t \tag{107}$$

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