# Market Neutrality and Climate Non-Neutrality: The Role for a Green QE

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**Abstract**

Tilting central bank asset purchases towards green bonds - Green QE - has been suggested as a way for central banks to mitigate their environmental impact while supporting the transition to a low carbon economy. I use a two sector E-DSGE model with financial frictions and imperfectly substitutable green and brown bonds to assess this proposal. The model is calibrated to the Euro Area at quarterly frequency, incorporating empirical findings on the brown tilt of the ECB portfolio under the status quo 'market neutrality' principle. Green QE is shown to achieve the same macro-stabilization outcomes as brown QE without the corresponding detrimental emissions. Moreover a shift in the ECB portfolio towards green bonds can lead to a substantial emissions decrease, at least in the short run. Turning to the question of transition risk, I show that a green QE rule can protect against the risk of a 'green recession' caused by a sudden, unexpected increase in the carbon price.

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# 1 Introduction

Preventing runaway climate change will undoubtedly require rapid and drastic action (IPCC, 2021). However, climate policy to date has lagged behind what is necessary even when commitments to emissions targets are made (UNEP, 2021). One reason for this is the 'tragedy of the horizion' identified by Carney (2015) - the impacts of climate change lie beyond the planning horizons of most actors while the costs of action are often born in the near future. Due to this lack of decisive action on climate from central governments, the financial sector - and central banks in particular - have begun to consider the physical and transition risks posed by climate change (Bolton et al., 2020; NGFS, 2020), and the effect of financial/monetary policy on emissions (Robins et al., 2021). Although some have voiced concern that an environmental mandate could undermine central bank independence (Hansen, 2022; Honohan, 2019), there has been a general move towards integrating climate considerations into central bank policy (Schnabel, 2021; NGFS, 2021a).

This paper addresses one suggestion for how central banks could integrate environmental targets into their operations - green QE, or the purchase of 'green' bonds by the central bank[1]. Green QE calls into question the 'market neutrality' principle which says that corporate bond purchases should not distort relative prices or costs of capital - QE should not interfere with the allocative market mechanism but rather provide uniform stimulus across the universe of eligible bonds. The ECB operationalizes the market neutrality principle by buying bonds in proportion to outstanding totals in the market.

However, in the presence of market failures, adhering to the market neutrality principle could reinforce inefficiencies that give rise to a sub-optimal allocation of resources (Schnabel, 2021). As climate risk isn't fully priced in, brown bonds may be over-weighted in the market portfolio (Campiglio et al., 2018). In fact, there is empirical evidence that brown bonds are over represented in the ECB corporate bond portfolio relative to capital shares - even abstracting from the implications of the climate externality for optimal allocations and take existing capital shares as given, the ECB holds a higher proportion of brown bonds than would be neutral. This is the key finding of Papoutsi et al. (2021). It has been argued that this brown tilt in ECB holdings is a problem as it amounts to an implicit subsidy towards the brown sector. Moreover, while the intention of QE is to stimulate overall growth, there is a suggestion in the literature that because transmission channels work imperfectly, there can be more benefit for the assets being purchased relative to other assets (Todorov, 2020; Joyce et al., 2010), and so a brown tilted QE could boost the brown sector relative to the green. This relatively larger stimulus to the brown sector is at odds with climate goals and could encourage increased debt issuance and expansion in the brown sector (Matikainen et al., 2017).

This paper contributes to this debate by addressing the following questions: Conditional on implementing expansionary QE, what should the sectoral composition of bonds purchased be? Could the central bank contribute to climate policy by reallocating its existing portfolio, i.e. by selling brown and buying green bonds? Could the central bank protect against transition risk by implementing a green QE rule?

I build a New-Keynesian E-DSGE model along the lines of Gertler and Karadi (2011) and Ferrari, A. and Nispi Landi, V. (2020). There are two sectors in the model - a brown sector whose output results in

[1]In section 2.11 I define brown bonds as those from the sectors responsible for more than 95% of emissions, and green bonds as those from all other sectors.

emissions of carbon dioxide, and a green sector whose output is 'clean'. Therefore there are both green and brown bonds. QE is defined as the purchase of corporate bonds by the central bank, and Green QE tilts the central bank's balance sheet towards the green sector[2]. As in Gertler and Karadi (2011), private banks face endogenously determined balance sheet constraints while the central bank is balance sheet unconstrained. This means that Wallace neutrality is broken and QE does affect production (Wallace, 1981).

Without an additional friction, the sectoral composition of the bond purchases would have no real effects. A temporary increase in the holdings of green bonds by the central bank, funded by selling brown bonds, would induce private banks to buy brown bonds until the returns on both are equal again as per the no-arbitrage condition. Therefore, I include an additional friction as per Ferrari, A. and Nispi Landi, V. (2020) which makes green and brown bonds imperfect substitutes via a quadratic cost which banks pay when the fraction of green bonds they hold is away from steady state. This prevents banks from fully exploiting the arbitrage opportunity arising when the return on green and brown bonds differs. Given the increased public scrutiny on the climate performance of financial institutions, it is reasonable to imagine that banks would suffer a cost if they tilted their portfolios too brown. Worries about transition risk and the potential for stranded assets may also induce banks not to fully exploit arbitrage opportunities on brown bonds. Moreover, as outlined above there is empirical evidence that QE results in more benefit for assets being purchased relative to other assets. One way of capturing this imperfect transmission is to make bonds imperfect substitutes.

The model is calibrated to the Euro Area at quarterly frequency. I synthesize empirical work, which shows that under the status quo central bank portfolios are heavily brown skewed (Papoutsi et al., 2021), with theoretical work which has so far assumed that the baseline is market neutral i.e. bonds are bought in proportion to capital shares. In order to match the brown tilt in the ECB portfolio as well as the empirical fact that green firms issue less corporate bonds, a wedge between green capital and eligible corporate bonds is introduced in steady state. A limitation of much existing work on climate policy over the business cycle has been a reliance on physically inaccurate and outdated emissions, atmospheric carbon, and temperature modelling. The Nordhaus-Heutel type environmental models often abstract from the permanent part of the stock of carbon, result in inaccurate warming delays and give carbon prices which are too low Dietz et al. (2021); Dietz and Venmans (2019). There is also much controversy over damage function specification with a wide range of empirical estimates of damages and deep uncertainty over the correct functional form. My approach is to instead use the robust scientific relationship between cumulative emissions and temperature, taking a 2 degree limit on temperature as given IPCC (2021). The environmental costs/benefits of different QE policies are then evaluated in terms of cumulative emissions created or avoided. I find that this approach, which is more in line with the climate science literature, along with modeling the baseline brown skew of the ECB portfolio results in larger gains from green QE.

With this model in place I perform three classes of experiments:

First, green QE is considered as macro-stabilization policy. I simulate an increase in the central bank's total assets (a QE shock) comparing three different scenarios. In the first, bonds are bought according to

[2]Public bond purchases are not considered here. There are questions as to how they would be conceptualized as 'green' or 'brown', and corporate bonds have been the focus of those pushing for a policy of green QE.

the ECB's operationalization of the market neutrality principle i.e. there is a brown tilt. In the second, the central bank buys only green bonds, and in the third, the central bank buys mostly green bonds. There is very little difference between the scenarios in terms of macroeconomic aggregate variables. However, the brown (status quo) scenario results in a substantial increase in emissions whereas the green scenarios keep emissions at steady state. I then consider QE in response to a financial crisis, specifying a QE rule which responds to spreads resulting from a capital quality shock. Green QE does just as well as a brown QE at stabilizing the economy but performs far better in terms of emissions.

Second, I ask whether changing the composition of bonds in the ECB portfolio could operate as climate policy. I simulate an increase in the proportion of green bonds held by the ECB, financed by selling brown bonds. Aggregate macroeconomic variables are not affected but a temporary increase in the proportion of green bonds results in a sharp, temporary reduction in emissions. A more persistent or permanent shock to the composition of the ECB portfolio results in a substantial emissions decline comparable with a moderate increase in the carbon price, at least in the short run.

Finally, I ask whether green QE could have any role in protecting against transition risk. As is common in papers considering the worst case scenario risks of asset stranding and bank equity losses, I modify the model to make capital sector specific and labour imperfectly substitutable across sectors Carattini et al. (2021). A permanent, unexpected increase in the carbon tax can result in a decline in green as well as brown output, but if a green QE rule is in place this 'green recession' effect is avoided. This removes a barrier to decisive climate action from central government. Turning to normative analysis using the climate modelling outlined above, green QE is shown to be preferable to brown QE, and tilting ECB bond holdings at least back to being in line with capital shares is desirable.

This paper contributes to the literature on monetary and climate policy over the business cycle. It joins a small but growing literature on the effects of green QE specifically. Over the last decade or so there has been a growing interest in integrating climate related issues into DSGE models, beginning with integration of a small Nordhaus-type climate model (Nordhaus, 2008) into an RBC model as in Heutel (2012). More recently, climate considerations have also been introduced into New-Keynesian models with nominal rigidities as in Annicchiarico and Di Dio (2015). Papers that explore the short run interactions of macroeconomic and climate policies have continued to use this framework (Annicchiarico et al., 2021; Boneva et al., 2021).

Most closely related to this paper is Ferrari, A. and Nispi Landi, V. (2020) which merges a model of financial frictions a la Gertler and Karadi (2011) with the environmental model of Heutel (2012). They simulate the effects of a green QE program relative to a market neutral one, and the effect of temporarily making the portfolio slightly more green and find quantitatively mild effects. Diluiso et al. (2021) also use a Gertler and Karadi (2011) type model with financial frictions, though instead of imperfectly substitutable green and brown bonds they specify an absconding rate which varies across sectors. They find that in response to an adverse financial shock originating in the fossil sector, a QE program tilted towards green assets can provide effective stimulus. A market neutral QE program also achieves this aim. Climate damages are disregarded, and emissions and temperature are not modeled meaning that welfare conclusions cannot be drawn. Benmir and Roman (2020) use a DSGE model to examine the role of QE in meeting

Paris Agreement Targets. They show that second best fiscal policy leads to a welfare wedge and a risk premium distortion. Macro-prudential policy favouring green sectors can boost green capital and output, while QE should be tilted towards brown sectors in order to reduce the effect of price volatility on risk premia. They attempt to update the climate modelling of Heutel (2012) to incorporate scientific advances in the understanding of the relationship between cumulative emissions and temperature, however their inclusion of a depreciation term to give the process a steady state means they get the counter-intuitive and physically inaccurate result that if steady state emissions fall, so too do *cumulative* emissions.

This paper is also closely related to Papoutsi et al. (2021) which uses microdata to show that the ECB's corporate bond purchase scheme is tilted towards brown sectors relative to capital shares. They also use a multisector growth model with a climate externality and financial frictions to show that the ECB's operationalization of market neutrality is only 'market neutral', i.e. doesn't distort relative costs of capital, under restrictive assumptions which are unlikely to hold in practice. Ferrari and Nispi Landi (2022) modifies Ferrari, A. and Nispi Landi, V. (2020) to consider how green QE could interact with a carbon tax over the course of the transition to a low carbon economy, and Ariby et al. (2022) develop a model with idiosyncratic return risk to run similar simulations. Both papers find that green QE complements a carbon tax though the marginal effects of green QE are lower in tandem with a carbon tax than without. Carattini et al. (2021) show that ambitious climate action can trigger instability in the banking sector and, in the presence of financial frictions, a contraction in the green as well as the brown sector can result.

To the best of our knowledge, an investigation of the role for green QE in a DSGE setting where the underlying brown tilt of the portfolio is accounted for is still missing. Likewise, an analysis of the role of green QE in crisis time with climate effects considered, and an investigation of the role for green QE in protecting against transition risk have not yet been done. This paper represents an attempt to fill these gaps.

## 2 Model

The core framework is an NK model, modified to include (i) financial frictions, (ii) separate green and brown sectors, and (iii) pollutant emissions and climate policies. The economy is composed of several types of agents: households who consume, save, and supply labour; final goods firms who combine the outputs of intermediate good firms; monopolistically competitive intermediate good firms who produce by combining green and brown inputs and are subject to Rotemberg adjustment costs; green and brown firms who produce by combining capital and labour; capital producers that repair depreciated capital, build new capital, and sell it to green and brown firms; banks that lend funds obtained from households to firms and are subject to adjustment costs when sectoral bond holdings are away from steady state; and a public sector setting monetary and climate policy. The model is therefore characterized by the following market failures: imperfect competition and sticky prices, a limited commitment constraint leading to financial friction, and a climate externality. The optimization problems of the agents follows. The full list of model equations is found in Appendix A and details of some of the derivations are confined to Appendix B.

## 2.1 Households

There is a continuum of households of measure unity. A constant fraction $1-f$ of households are workers and $f$ are bankers. The probability of a banker remaining a banker in the following period is $\chi$ which is independent of history so that the average survival time for a banker in any given period is $\frac{1}{1-\chi}$. Each banker manages a bank and profits are transferred to households. Idiosyncratic risk is completely shared among households which permits use of the representative agent framework.

The representative household solves the following optimization problem:

$$\max_{\{c_t,N_t,d_t\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi}\right)$$

$$s.t. c_t + d_{Ht} = \frac{r_{t-1}}{\pi_t} d_{Ht-1} + w_t h_t - t_t + \Gamma_t$$

where $c_t$ denotes consumption of the final good, $N_t$ is hours worked, $d_{Ht}$ is the sum of bank deposits $d_t$ and public bonds $d_{Pt}$ held where both assets yield a nominal interest rate $r_t$.[3] $w_t$ is hourly real wage, $\pi_t$ is the gross inflation rate, $t_t$ denotes lump sum taxes and $\Gamma_t$ are profits from ownership of firms and banks.

The maximization problem of the household yields the following FOCs:

$$c_t^{-\sigma} = \lambda_t \tag{1}$$

$$N_t^{\varphi} = \lambda_t w_t \tag{2}$$

$$\lambda_t = \beta \mathbb{E}_t \lambda_{t+1} \frac{r_t}{\pi_{t+1}} \tag{3}$$

where $\lambda_t$ is the Langrange multiplier i.e. the marginal utility of consumption. Substitution yields a standard Euler equation and a labour supply equation (Appendix A).

## 2.2 Final Good Firms

The representative final good firm uses a CES aggregator to produce the final good $y_t$. The problem of the final good firm is:

$$\max_{y_t,\{y_t(i)\}_{i\in[0,1]}} p_t y_t - \int_0^1 p_t(i) y_t(i) di$$

.

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

where $p_t$ is the CPI, $y_t(i)$ is an intermediate good produced by intermediate firm i, and the price of that good is $p_t(i)$. This problem yields the following demand function $\forall i$ :

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

[3] i.e. they are perfect substitutes.

### 2.3 Intermediate Good Firms

There are a continuum of intermediate good firms indexed i. Each firm produces a differentiated input $y_t(i)$ as follows:

$$y_t(i) = y_t^I(i) \tag{5}$$

where $y_t^I$ is a CES aggregator of green production $y_t^G$ and brown production $y_t^B$.

$$y_t^I(i) = \left[(1-\zeta)^{\frac{1}{\xi}} \left(y_t^G(i)\right)^{\frac{\xi-1}{\xi}} + \zeta^{\frac{1}{\xi}} \left(y_t^B(i)\right)^{\frac{\xi-1}{\xi}}\right]^{\frac{\xi}{\xi-1}} \tag{6}$$

#### 2.3.1 Optimal Input Problem

Intermediate firm i solves the following cost-minimization problem to choose the optimal input combination:

$$\min_{y_t^B(i), y_t^G(i)} \quad p_t^G y_t^G(i) + p_t^B y_t^B(i)$$
$$\text{s.t.} \quad \left[(1-\zeta)^{\frac{1}{\xi}} \left(y_t^G(i)\right)^{\frac{\xi-1}{\xi}} + \zeta^{\frac{1}{\xi}} \left(y_t^B(i)\right)^{\frac{\xi-1}{\xi}}\right]^{\frac{\xi}{\xi-1}} = y_t^I(i),$$

where $y_t^I(i)$ is a given level of production and $p_t^G$ and $p_t^B$ are the price of green and brown production respectively, both expressed relative to the CPI. The problem yields the following demand functions:

$$y_t^G(i) = (1-\zeta) \left(\frac{p_t^G}{p_t^I}\right)^{-\xi} y_t^I(i) \tag{7}$$

$$y_t^B(i) = \zeta \left(\frac{p_t^B}{p_t^I}\right)^{-\xi} y_t^I(i) \tag{8}$$

Where $p_t^I$ is the real MC of the firm:

$$p_t^I = \left[(1-\zeta) \left(p_t^G\right)^{1-\xi} + \zeta \left(p_t^B\right)^{1-\xi}\right]^{1-\xi} \tag{9}$$

#### 2.3.2 Optimal Price Problem

Firms operate in monopolistic competition, setting prices subject to the demand of the final good firm. They are also subject to Rotemberg adjustment costs i.e. firm i pays a quadratic cost in nominal terms whenever it adjusts the growth of its price from the benchmark level $\bar{\pi}$.

Therefore, firm i's intertemporal maximization problem is:

$$\max_{\{p_t(i)\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[ \left(\frac{p_t(i)}{p_t}\right)^{-\varepsilon} \left(\frac{p_t(i)}{p_t} - p_t^I\right) y_t - \frac{\kappa_P}{2} \left(\frac{p_t(i)}{p_{t-1}(i)} - \bar{\pi}\right)^2 y_t \right] \right\}$$

where $\lambda_t$ is the marginal utility of households. In a symmetric equilibrium (all firms set the same price $p_t(i) = p_t$), this problem yields a non-linear new-Keynesian Phillips Curve:

$$\pi_t\left(\pi_t-\bar{\pi}\right)=\beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{t+1}\left(\pi_{t+1}-\bar{\pi}\right)\frac{y_{t+1}}{y_t}\right]+\frac{\varepsilon}{\kappa_P}\left(p_t^I-\frac{\varepsilon-1}{\varepsilon}\right) \tag{10}$$

where $\pi_t$ is the inflation rate, $\frac{p_t}{p_{t-1}}$. If $\kappa_P>0$ changing prices is costly and the classical dichotomy is broken.

## 2.4 Brown Firms

Brown firms produce an output that is used as an input by intermediate firms using a Cobb-Douglas production function:

$$y_t^B=a_t^B(s_t^{kB}k_{t-1}^B)^\alpha(N_t^B)^{(1-\alpha)} \tag{11}$$

where $s_t^{kB}$ is a capital quality term used to model financial crises. Exogenous variation in the value of capital follows an autoregressive process where $\upsilon_t^{sB}\sim N\left(0,\sigma_{sB}^2\right)$ is the associated exogenous shock. $a_t^B$ is TFP which also follows an autoregressive process where $\upsilon_t^a\sim N\left(0,\sigma_a^2\right)$ is a technology shock and $\bar{a}_t^B$ is steady state TFP.

$$\log(s_t^{kB})=\rho_s\log(s_{t-1}^{kB})-\upsilon_t^{sB} \tag{12}$$

$$\log(a_t^B)=(1-\rho_a)\log(\bar{a}_t^B)+\rho_a\log(a_{t-1})+\upsilon_t^a \tag{13}$$

Brown firms issue bonds to finance capital expenditure:

$$b_t^B=q_tk_t^B \tag{14}$$

where $q_t$ is the price of the capital good. The bond is expressed in real terms and pays a real interest rate $r_t^B$. Brown firms buy capital from capital producers which buy back non-depreciated capital, implying a rental rate of capital for brown firms of:

$$r_{kt}^B=[r_t^Bq_{t-1}-(1-\delta)q_t] \tag{15}$$

Emissions in gigatonnes of carbon dioxide ($F_t$) are proportional to brown output and brown firms pay a tax $\tau^F$ on their emissions. They also have the option to invest in an abatement technology to reduce their emissions at cost $Z$:

$$F_t=\upsilon_b(1-\mu_{ct})y_t^B \tag{16}$$

$$Z_t=\theta_1\mu_{ct}^{\theta_2}y_t^B$$

where $\mu_{ct}$ is the proportion of emissions abated, and $\theta_1$ and $\theta_2$ are abatement cost parameters. Therefore, profits are given by:

$$\Gamma_t^B=p_t^By_t^B-w_tN_t^B-r_{kt}^Bk_{t-1}^B-Z_t-\tau_t^FF_t$$

and optimization gives first order conditions with respect to labour demand, capital demand, and abatement:

$$w_tN_t^B=(1-\alpha)y_t^B[p_t^B-\theta_1\mu_{ct}^{\theta_2}-\tau_t^F(1-\mu_{ct})\upsilon_b] \tag{17}$$

$$r_{kt}^{B}k_{t-1}^{B} = \alpha.y_t^B[p_t^B - \theta_1\mu_{ct}^{\theta_2} - \tau_t^F(1-\mu_{ct})\upsilon_b] \tag{18}$$

$$\tau_t^F = \frac{\theta_1\theta_2\mu_{ct}^{\theta_2-1}}{\upsilon_b} \tag{19}$$

### 2.5 Green Firms

Green firms similarly produce an output using a Cobb-Douglas production function.

$$y_t^G = a_t^G(s_t^{kG}k_{t-1}^G)^{\alpha}(N_t^G)^{(1-\alpha)} \tag{20}$$

$$\log(s_t^{kG}) = \rho_s \log(s_{t-1}^{kG}) - v_t^{sG} \tag{21}$$

$$\log(a_t^G) = (1-\rho_a)\log(\bar{a}_t^G) + \rho_a \log(a_{t-1}) + v_t^a \tag{22}$$

where $v_t^{sG} \sim N\left(0, \sigma_{sG}^2\right)$ and $v_t^a \sim N\left(0, \sigma_a^2\right)$

They issue bonds to finance capital expenditure and face a rental rate of capital as follows:

$$b_t^G = q_t k_t^G \tag{23}$$

$$r_{kt}^G = [r_t^G q_{t-1} - (1-\delta)q_t] \tag{24}$$

Unlike brown firms, green output is not related to emissions and so green firms do not pay a carbon tax. Therefore profits are given by:

$$\Gamma_t^G = p_t^G y_t^G - w_t N_t^G - r_{kt}^G k_{t-1}^G$$

and capital and labour demand are:

$$w_t N_t^G = (1-\alpha)p_t^G y_t^G \tag{25}$$

$$r_{kt}^G k_{t-1}^G = \alpha.p_t^G y_t^G \tag{26}$$

A key feature of the data on ECB bond holdings and the corporate bond market is that although the green sector has a large capital share, green corporate bonds only account for a small proportion of the corporate bond market (Papoutsi et al., 2021).[4] In steady state of the model however, Tobin's q is 1 so $b^G = k^G$ i.e. the share of green bonds is equal to the green capital share. Therefore, in order to better capture the realities of the European corporate bond market I introduce a wedge:

$$b_t^{GE} = \upsilon_g b_t^G \tag{27}$$

where $b_t^{GE}$ represents eligible green corporate bonds and $\upsilon_g < 1$ is calibrated to reconcile the capital share and bond share discrepancy. $b_t^G - b_t^{GE}$ can then be interpreted as other sources of funding which are not

[4] The European corporate bond market is relatively underdeveloped and green firms tend to be smaller and individually less capital intensive. Brown firms tend to have more tangible assets which can be used as collateral and so they issue a higher proportion of corporate bonds.

corporate bonds eligible for ECB purchase. [5]

## 2.6 Capital Producers

Capital producers buy output from final good firms and non-depreciated capital from intermediate firms in order to produce physical capital. This physical capital is then purchased by green and brown firms. Capital producers solve the following problem:

$$\max_{\{i_t,k_t\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[ q_t k_t - (1-\delta) q_t s_t^k k_{t-1} - i_t \right] \right\}$$

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

where $k_t$ is aggregate capital in the economy, $i_t$ denotes investment and $\kappa_I$ is an investment adjustment cost parameter as in Christiano et al. (2005), included to improve the dynamic performance of the model [6].

The first order condition reads:

$$\begin{aligned} 1 = & q_t \left\{ 1 - \frac{\kappa_I}{2} \left( \frac{i_t}{i_{t-1}} - 1 \right)^2 - \kappa_I \frac{i_t}{i_{t-1}} \left( \frac{i_t}{i_{t-1}} - 1 \right) \right\} + \\ & + \beta \mathbb{E}_t \left[ \frac{\lambda_{t+1}}{\lambda_t} q_{t+1} \left( \frac{i_{t+1}}{i_t} \right)^2 \kappa_I \left( \frac{i_{t+1}}{i_t} - 1 \right) \right] \end{aligned} \tag{28}$$

This can be interpreted as the Tobin's Q, giving the present discounted value of adjustment costs from investing in an additional unit of capital.

## 2.7 Banks

As outlined above, banks are subject to two frictions. Firstly, as in Gertler and Karadi (2011), banks are balance sheet constrained (while the central bank is unconstrained) which means that Wallace neutrality is broken. Secondly, Banks pay a quadratic adjustment cost when the proportion of green bonds held is away from steady state $b^*$ as in Ferrari, A. and Nispi Landi, V. (2020). This means that QE can affect green and brown sectors differently depending on the sectoral composition of bonds purchased.

There is a continuum of banks indexed by j. The balance sheet of bank j is given by:

$$b_{Ft}^B(j) + b_{Ft}^G(j) = n_t(j) + d_t(j) \tag{29}$$

where $b_{Ft}^B(j)$ and $b_{Ft}^G(j)$ are green and brown bonds held by bank j; $n_t(j)$ is bank j's net worth which accumulates through profits, and $d_t(j)$ is deposits held at bank j.

[5] Another way of matching the data would be to more explicitly model other sources of funding - equity and loans. To do so adds complexity without providing much insight to the results discussed here. For full discussion of green firms funding decisions see Papoutsi et al. (2021)

[6] I assume here that capital quality is common across sectors: $s_t^{kB} = s_t^{kG}$

Net worth increases with profits, i.e. interest earned on bond holdings less adjustment costs and interest payments made on deposits:

$$n_t(j) = r_t^B b_{Ft-1}^B(j) + r_t^G b_{Ft-1}^G(j) - \frac{r_{t-1}}{\pi_t} d_{t-1}(j) - \frac{\kappa_{FG}}{2} n_{t-1}(j) \left( \frac{b_{Ft-1}^G(j)}{b_{Ft-1}(j)} - b^* \right)^2 \tag{30}$$

where $b_{Ft}(j) \equiv b_{Ft}^B(j) + b_{Ft}^G(j)$ denotes total assets of bank $j$ and the last term is the quadratic adjustment cost faced by the bank. $\kappa_{FG}$ specifies how imperfectly substitutable green and brown bonds are. If $\kappa_{FG} = 0$, green and brown bonds are perfect substitutes and the banking model collapses to that of Gertler and Karadi (2011).

$\beta^i \Lambda_{t,t+i}$ is the discount factor applying in $t$ to earnings in $t+i$, where $\Lambda_{t,t+i} \equiv \frac{\lambda_{t+i}}{\lambda_t}$. With probability $(1-\chi)$ banker $j$ exits the market. In this case the banker gets $n_{t+1}(j)$ at the beginning of period $t+1$ which is transferred to households. With probability $\chi$, banker $j$ continues as a banker and therefore gets the continuation value. The value of bank $j$ is therefore defined as follows:

$$V_{jt}\left(n_t(j)\right) = \max \mathbb{E}_t \left[ \sum_{i=0}^{\infty} (1-\chi)\chi^i \beta^{i+1} \Lambda_{t,t+1+i} n_{t+1+i}(j) \right]$$

As in Gertler and Karadi (2011) it is assumed that in every period bankers can divert a fraction $\theta$ of available funds. If they do so, depositors can recover the remaining fraction of the assets. This is the 'limited commitment' constraint. As a result, depositors are willing to lend to bankers if and only if the value of the bank is not lower than the fraction of divertable funds:

$$V_{jt}\left(n_t(j)\right) \geq \theta b_{Ft}(j)$$

The problem of the bank is to maximize their value function subject to their net worth condition and the incentive constraint. Following Ferrari, A. and Nispi Landi, V. (2020) I consider an equilibrium where the incentive constraint binds and each bank chooses the same leverage ratio. The first order conditions for the banks then read:[7]

$$l_t = \frac{\mathbb{E}_t \left\{ \beta \frac{\lambda_{t+1}}{\lambda_t} \nu_{t+1} \left[ \left( r_{t+1}^G - r_{t+1}^B \right) l_t^G + \frac{r_t}{\pi_{t+1}} - \frac{\kappa_{FG}}{2} \left( \frac{l_t^G}{l_t} - b^* \right)^2 \right] \right\}}{\theta - \mathbb{E}_t \left\{ \beta \frac{\lambda_{t+1}}{\lambda_t} \nu_{t+1} \left( r_{t+1}^B - \frac{r_t}{\pi_{t+1}} \right) \right\}} \tag{31}$$

$$\frac{\kappa_{FG}}{l_t} \left( \frac{l_t^G}{l_t} - b^* \right) = \frac{\mathbb{E}_t \left\{ \beta \frac{\lambda_{t+1}}{\lambda_t} \nu_{t+1} \left( r_{t+1}^G - r_{t+1}^B \right) \right\}}{\mathbb{E}_t \left\{ \beta \frac{\lambda_{t+1}}{\lambda_t} \nu_{t+1} \right\}} \tag{32}$$

where $l_t = \frac{b_{Ft}}{n_t}$ and $l_t^G = \frac{b_{Ft}^G}{n_t}$ are the bank's leverage and green leverage ratios respectively. The second optimality condition is new compared to Gertler and Karadi (2011) and emerges as a result of the quadratic adjustment cost introduced by Ferrari, A. and Nispi Landi, V. (2020). If $\kappa_{FG}$ is equal to 0 then the expected

[7] for derivation see Appendix B.

spread is 0 so the second condition is trivially satisfied and the first condition collapses to that in Gertler and Karadi (2011) i.e. it says that the assets the bank can acquire depends on it's equity capital. If the cost parameter $\kappa_{FG}$ is larger than zero, however, arbitrage between green and brown bonds is not costless and complete. Given that changing asset composition is costly, an increase in the spread will not necessarily be brought back to zero via arbitrage.

$\nu_t$ can be interpreted as the bank's discount factor:

$$\begin{aligned}\nu_t =&(1-\chi)+\\ &+\chi\beta\mathbb{E}_t\left\{\frac{\lambda_{t+1}}{\lambda_t}\nu_{t+1}\left[\left(r^G_{t+1}-r^B_{t+1}\right)l^G_t+\left(r^B_{t+1}-\frac{r_t}{\pi_{t+1}}\right)l_t+\frac{r_t}{\pi_{t+1}}-\frac{\kappa_{FG}}{2}\left(\frac{l^G_t}{l_t}-b^*\right)^2\right]\right\}\end{aligned} \tag{33}$$

As in Ferrari, A. and Nispi Landi, V. (2020), a first order approximation of equation 32 yields the following expression:

$$\left(\tilde{b}^G_{Ft}-\tilde{b}_{Ft}\right)=\gamma\mathbb{E}_t\left(r^G_{t+1}-r^B_{t+1}\right)$$

where $\gamma \equiv \frac{l}{\kappa_{FG}(1-\zeta)}$, variables with a tilde are percentage deviations from steady state and variables without the time subscript are steady state values. Therefore, $\gamma$ has the interpretation of the percentage increase in the share of green bonds out of total banking bonds resulting from a 100 basis points increase in the expected spread between green and brown bonds. An increase in the spread between green and brown bonds induces banks to replace brown bonds with green bonds, however when $\gamma < \infty$ i.e. $\kappa_{FG} > 0$ the adjustment cost means that arbitrage does not necessarily bring the spread back to zero.

Aggregate net worth can be split between net worth of new bankers and of old bankers.

$$n_t = n_{ot} + n_{yt}.$$

Since a fraction $\chi$ of bankers in period $t-1$ survive until period $t$, it holds:

$$n_{ot}=\chi\left[\left(r^G_t-r^B_t\right)l^G_{t-1}+\left(r^B_t-\frac{r_{t-1}}{\pi_t}\right)l_{t-1}+\frac{r_{t-1}}{\pi_t}-\frac{\kappa_{FG}}{2}\left(\frac{l^G_{t-1}}{l_{t-1}}-b^*\right)^2\right]n_{t-1}.$$

We assume that households transfer a share of assets of exiting bankers $\frac{\eta}{1-\chi}$ to new bankers, in order to start business:

$$n_{yt} = \eta b_{Ft}.$$

Therefore, we can derive an expression for the evolution of aggregate bank net worth:

$$n_t=\chi\left[\left(r^G_t-r^B_t\right)l^G_{t-1}+\left(r^B_t-\frac{r_{t-1}}{\pi_t}\right)l_{t-1}+\frac{r_{t-1}}{\pi_t}-\frac{\kappa_{FG}}{2}\left(\frac{l^G_{t-1}}{l_{t-1}}-b^*\right)^2\right]n_{t-1}+\eta b_{Ft} \tag{34}$$

## 2.8 Climate dynamics

As outlined above, emissions in Gt of carbon dioxide are proportional to brown output taking abatement investment into account. Cumulative emissions ($E_t$) are defined as:

$$E_{t+1} = E_t + F_t + F* \tag{35}$$

where F* is rest of world emissions. Temperature ($T_t$) is linearly related to cumulative emissions:

$$T_t = T_0 + \iota E_t \tag{36}$$

where $\iota$ is the Transient Climate Response to Cumulative Carbon Emissions (TCRE)[8].

Due to the unit root in the cumulative emissions process, this specification of climate dynamics cannot easily be fit into a DSGE model. However, alternative approaches are unsatisfactory. Nordhaus-Heutel type damages abstract from the permanent part of the stock of atmospheric carbon. These models result in inaccurate climate dynamics and biased policy recommendations (Dietz et al., 2021). An attempt to give the cumulative emissions process a steady state by imposing a small depreciation term as in Benmir and Roman (2020) results in the incorrect implication that if quarterly emissions fall below steady state then cumulative emissions also decline.

Therefore, as damages are small over the time period considered anyway[9], I abstract from damages and do not include a climate feedback into TFP or utility. Instead, I use this specification of climate dynamics to compare the environmental performance of the different policies in terms of emissions budgets, temperature caps, and the social cost of carbon. Further discussion of this follows in section 4.

## 2.9 Policy

The central bank and government are treated as a single entity and investment in corporate bonds by the public sector is financed through public bonds $d_{Pt}$:

$$b^G_{Pt} + b^B_{Pt} = d_{Pt} \tag{37}$$

I assume a consolidated budget constraint and constant public consumption financed by lump sum taxation, carbon tax revenues, and intermediation profits.

$$g_t = t_t + (r^G_t - \frac{r_{t-1}}{\pi_t})b^G_{Pt-1} + (r^B_t - \frac{r_{t-1}}{\pi_t})b^B_{Pt-1} + \tau^F_t F_t \tag{38}$$

The central bank sets the nominal interest rate according to a standard Taylor Rule:

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r}\right)^{\rho_r} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_r} \tag{39}$$

[8]This captures the robust physical finding that the relationship between temperature and cumulative emissions is roughly constant over time.

[9]and there is deep disagreement over how they should be correctly modelled

where $\bar{\pi}$ is the steady state rate of inflation, and $y$ is steady state output. The central bank also sets the share of bonds held by the public - QE policy:

$$\mu = \frac{b_{Pt}}{b_{Et}} \tag{40}$$

where $b_{Et} = b_t^{GE} + b_t^B$ is the total amount of eligible corporate bonds, and $b_{Pt} = b_{Pt}^G + b_{Pt}^B$ is the total amount of these bonds held by the public sector.

I specify a rule for QE policy which responds to spreads and so targets the financial friction in the banking sector as in Gertler and Karadi (2011):

$$\frac{\mu_t}{\bar{\mu}} = \left(\frac{\mu_{t-1}}{\bar{\mu}}\right)^{\rho_\mu} \left[\left(\frac{sp_t^G}{sp}\right)^{\phi_\mu} \left(\frac{sp_t^B}{sp}\right)^{\phi_\mu}\right]^{1-\rho_\mu} \exp\left(v_t^{qe}\right) \tag{41}$$

where $\bar{\mu}$ is the QE target, $sp_t^G$ and $sp_t^B$ are credit spreads over the risk-free interest rate:

$$sp_t^G = \mathbb{E}_t\left[r_{t+1}^G - \frac{r_t}{\pi_{t+1}}\right] \tag{42}$$

$$sp_t^B = \mathbb{E}_t\left[r_{t+1}^B - \frac{r_t}{\pi_{t+1}}\right] \tag{43}$$

and $(v_t^{qe})$ is a normally distributed QE shock.

The central bank also has control over Green QE policy. This is modelled as the proportion of bonds held by the public sector that are green:

$$\mu_t^G = \frac{b_{Pt}^G}{b_{Pt}} \tag{44}$$

## 2.10 Market Clearing

To close the model I impose the following market clearing conditions for labour, capital, goods and bonds:

$$N_t = N_t^G + N_t^B \tag{45}$$

$$k_t = k_t^G + k_t^B \tag{46}$$

$$y_t = c_t + i_t + g + \frac{\kappa_P}{2}\left(\pi_t - \bar{\pi}\right)^2 y_t + \frac{\kappa_{FG} n_{t-1}}{2}\left(\frac{l_{t-1}^G}{l_{t-1}} - b^*\right)^2 + Z_t \tag{47}$$

$$b_t = b_t^G + b_t^B \tag{48}$$

$$b_t^B = b_{Ft}^B + b_{Pt}^B \tag{49}$$

$$b_t^G = b_{Ft}^G + b_{Pt}^G \tag{50}$$

## 2.11 Calibration

The model is calibrated to the Euro Area (EA) at quarterly frequency for a number of reasons. First of all, the ECB has announced plans to decarbonise its corporate bond holdings rendering the discussion relevant [10]. Second, the Papoutsi et al. (2021) empirical results on the brown tilt of QE are from ECB data which allows me to be precise about the scope of the brown tilt and potential for instead tilting green. Third, the ECB has historically engaged in large corporate bond purchases and is a large player in the corporate bond market which means the sectoral composition of bond purchases could have important environmental implications. Finally, calibration to the EA enables me to keep my results comparable with those presented by Ferrari, A. and Nispi Landi, V. (2020).

The calibration strategy is as follows: first, I take standard values from the New Keynesian literature. Then I set the remaining parameters to match relevant moments in the data and the empirical results outlined in Papoutsi et al. (2021). The table below summarizes the results of this calibration strategy which is discussed in this section.

The discount rate is set to 0.99. Along with the calibrated steady state level of inflation this implies an annualized steady state real interest rate of about 2 percent in line with the data. Both $\sigma$ and $\phi$ are set to standard values in the literature of 2 and 1 and respectively. The elasticity of substitution of differentiated goods is set to 6 in line with Ferrari, A. and Nispi Landi, V. (2020). While this is a little high compared to the literature, the results are not sensitive to reducing it. Price adjustment costs are set to match a Calvo duration of 0.75, and capital shares to 0.33. Steady state capital quality and TFP are normalized to 1. Investment adjustment costs are set to 2.48, and the depreciation rate to 0.0025.

Papoutsi et al. (2021) show that more than 95 percent of scope 1 emissions come from agriculture, manufacturing, utilities and transport sectors in the EU [11]. Therefore, I identify these sectors as brown and the rest of the economy as green. The capital income of these 'brown' sectors is about 35 percent of total capital income, implying a zeta of 0.35.[12] In order to reconcile the discrepancy between the green sector capital share and the green corporate bond market share documented in Papoutsi et al. (2021), I set $\upsilon_G$ to 0.285. This results in a steady state bond share of 0.33 in line with the evidence.

The elasticity of substitution between green and brown inputs is set to 1 as in Ferrari, A. and Nispi Landi, V. (2020), implying that the intermediate production function is Cobb-Douglas. Some papers in the literature, for example Carattini et al. (2021) set this parameter to the higher value of 2 on the basis of the empirical results presented by Papageorgiou et al. (2017). However, the interpretation of this estimate is the elasticity of substitution between green and brown *energy* inputs which is not the interpretation I give to the green and brown sectors here. There is also an argument to be made that the elasticity should be lower, with the interpretation that green and brown inputs are not easily substituted. I set the elasticity to 1 to balance these competing claims and present sensitivity analysis in Appendix C.

Global emissions of carbon dioxide were close to 37 gigatonnes in both 2019 and 2021 [13] (GCP, 2022).

[10] https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr220919 fae53c59bd.en.html

[11] These sectors account for an even higher share once scope 2 and 3 emissions are included.

[12] This figure is relatively standard for the literature. For example, Carattini et al. (2021) set the brown weight to 0.3326 on the basis that the income share of the green sector to total output is about 70 percent.

[13] Emissions in 2020 were unusually low due to the pandemic and lockdowns.

The EA accounts for about 6 percent of global emissions implying quarterly emissions of 0.555 Gt. The emissions intensity of output, $\upsilon_b$ is set to target $F = 0.555$ given $\zeta = 0.35$. $\iota$ is the transient climate response to carbon emissions, or the amount by which temperature in Celsius increases when cumulative emissions increases by a gigatonne. Working Group I of the IPCC sixth assessment report estimated a likely range for this value between 0.001 and 0.0023 (IPCC, 2021). I set $\iota$ to the midpoint, and do the calculations in section 4 for the whole range. The IPCC estimate of the increase in global average surface temperature since pre-industrial times - 1.07 degrees Celsius - is used as the value for $T_0$.

The bank survival probability $\chi$ is set to 0.972, implying that on average banks survive for 9 years. The divertable proportion of assets, $\theta$ is set to target a steady state leverage ratio of the banking sector of 4.5, and the new wealth for banks $\eta$ is set to target annualized credit spreads of 90 basis points. This results in values for the banking parameters in line with those used in the literature. $\kappa_{FG}$ is a key parameter in this model, measuring the cost of arbitrage. No good empirical estimates for this reduced form friction exist and estimation attempts are complicated by lack of data and the specification that the friction holds only away from steady state. However, the result that green QE is preferable in terms of emissions depends only on a value greater than 0 i.e. some imperfect substitutability, which seems reasonable. For now, in order to make my results comparable with Ferrari, A. and Nispi Landi, V. (2020), I set $\kappa_{FG}$ such that a reduction of 100 basis points in the green-brown spread leads banks to reduce their green holdings by about 10 percent. In my model this implies a value of 0.6923. I run simulations with different values of this parameter for illustrative purposes, and these results are presented in Appendix C.

The steady state inflation rate is set to 1.005, equivalent to the 2 percent yearly ECB target. Public spending is set to target a steady state proportion of 0.2 out of total output. I normalize the carbon price to €0. Therefore the interpretation of any higher value of $\tau^F$ is an increase in the price above the current [14] value of around €88 per tonne. The Taylor Rule coefficients are set to 1.5 and 0 and the response of QE to the spread is initially set to 0 though I do run simulations where it is set at above 0.

Following Ferrari, A. and Nispi Landi, V. (2020), I set $\mu$, the proportion of bonds held by the ECB, to 0.1. I present a robustness check in Appendix C which instead sets $\mu$ higher in line with the Papoutsi et al. (2021) result that the ECB buys between 20 and 40 percent of newly issued bonds[15]. I set $\mu_G$ to match the Papoutsi et al. (2021) result on the brown tilt of the ECB portfolio. They show that the ECB portfolio is strongly brown tilted. Most of this tilt is accounted for by the fact that green corporate bonds make up a small proportion of total corporate bonds, however the ECB portfolio is still somewhat brown skewed taking this into account [16].

[14] May 2022

[15] For the results in section 3.1 the size of $\mu$ doesn't matter as long as the size of the shock in terms of the value of capital is the same. For the results in 3.2 a larger value for $\mu$ results in bigger effects from Green QE.

[16] See Papoutsi et al. (2021) figures 3 and 4.

| Parameter | Description | Value | Notes |
|---|---|---|---|
| | Households | | |
| $\beta$ | Discount factor | 0.99 | |
| $\sigma$ | Inverse of EIS | 2 | |
| $\varphi$ | Inverse of Frisch elasticity | 1 | |
| | Final Firms | | |
| $\varepsilon$ | Elas. of subst. differentiated goods | 6 | |
| | Intermediate Firms | | |
| $\zeta$ | Weight of brown good | 0.35 | Papoutsi et al |
| $\xi$ | Elas. of subst. brown-green good | 1 | |
| $\kappa_P$ | Price adjustment costs | 26.8638 | $3/4$ Calvo duration |
| | Green and Brown firms | | |
| $\alpha$ | Share of capital in production | 0.33 | |
| $sk^B, sk^G$ | Steady State Capital Quality | 1 | |
| $a^G, a^B$ | Steady State TFP | 1 | |
| $\upsilon_G$ | SS fraction of green capital in bonds | 0.285 | Papoutsi et al |
| | Capital producers | | |
| $\kappa_I$ | Investment adjustment cost | 2.48 | Christiano et al |
| $\delta$ | Depreciation rate | 0.025 | |
| | Banks | | |
| $\theta$ | Divertable proportion of assets | 0.3442 | to target l=4.5 |
| $\chi$ | Bank survival probability | 0.972 | |
| $\eta$ | Wealth for new banks | 0.0019 | to target sp=0.00225 |
| $\kappa_{FG}$ | Bank adj. cost | 0.6923 | Ferrari and Landi (2020) |
| | Climate Dynamics | | |
| $\upsilon_b$ | Carbon intensity of output | 0.6857 | to target F=0.555 GT CO2 |
| $F^*$ | Rest of World Emissions | 8.51 | GT CO2 |
| $\theta_1, \theta_2$ | Abatement cost | $0.0335, 2$ | Nordhaus |
| $\iota$ | TCRE | 0.0017 | IPCC |
| $T_0$ | Initial Temperature | 1.07 | IPCC |
| | Policy | | |
| $\bar{\pi}$ | SS inflation | 1.005 | |
| $\mu, \mu_G$ | SS QE and GQE | $0.1, 0.3$ | |
| $\tau^F$ | Carbon tax | 0 | normalization |
| $g$ | Public spending | 0.2352 | to target g/y=0.2 |
| $\phi_\pi, \phi_y$ | Taylor rule coefficients | $1.5, 0$ | |
| $\phi_\mu$ | QE rule coefficient | 0 | |
| $\rho_r, \rho_\mu, \rho_G$ | Inertia of rules | 0.8 | |
| $\rho_a, \rho_s$ | Persistence of shocks | $0.95, 0.66$ | |

Figure 1: Calibration Summary

# 3 Results

## 3.1 Green QE as macro-stabilization policy

If the ECB engages in corporate QE, what should the sectoral composition of its bond purchases be? In particular, is it possible to make an improvement over the status quo wherein the asset purchase program tilts heavily towards brown bonds? In this section I consider first a QE shock, then a QE response to a capital quality shock using a QE rule, and finally the case of QT. Impulse response functions are obtained by solving the first order approximation of the model around the steady state.

### 3.1.1 QE Shock

Figure 2 shows the effect of a 10% shock to the QE parameter $\mu$, in line with Ferrari, A. and Nispi Landi, V. (2020). This is a temporary increase in the central bank's assets financed by debt issuance. In the first scenario (dotted black line), purchases are made according to the ECB's operationalization of the market neutrality principle i.e. the expansion is heavily brown tilted. In the second (dashed green line), the central bank buys only green bonds, and in the third (solid blue line) the central bank buys mostly (90%) green bonds. In all three scenarios, the QE shock puts downward pressure on the interest rate which results in an increase in production. The rise in total output creates inflationary pressure, and though consumption is depressed on impact it later increases relative to steady state. The difference between the three QE policies on output, consumption and inflation is invisible - all three are able to achieve the same aggregate macroeconomic effects.

When QE is brown tilted, the interest rate on brown bonds falls. Therefore, banks reduce brown and buy green bonds. However they don't fully adjust to offset the central bank's intervention due to adjustment costs: brown output increases, and although green output increases on impact, it goes on to fall below steady state. Emissions also spike with brown output and remain above steady state. In contrast, when QE is green tilted, green output increases while brown output, and therefore emissions, fall. The green QE is therefore just as good as brown QE in terms of aggregate macro outcomes but performs better in terms of emissions. The small contraction in brown output caused by the green QE can be mostly avoided by buying a small amount of brown bonds. The gain in terms of emissions from switching from the baseline to a green tilt is far larger than that presented in Ferrari, A. and Nispi Landi, V. (2020). This is because they assume that the baseline ECB portfolio is in line with capital shares. The emissions difference is also bigger if we consider larger QE shocks similar in size to those conducted in the wake of the global financial crisis. I consider this case in the next section.

As shown by Ferrari, A. and Nispi Landi, V. (2020), the sectoral composition has real effects only when bonds are imperfectly substitutable. As long as $\kappa_{FG} > 0$ green QE performs better in terms of emissions than brown tilted QE, and achieves the same aggregate macro outcomes. See section 3.4 for a discussion of the effects of changing $\kappa_{FG}$ on the results.

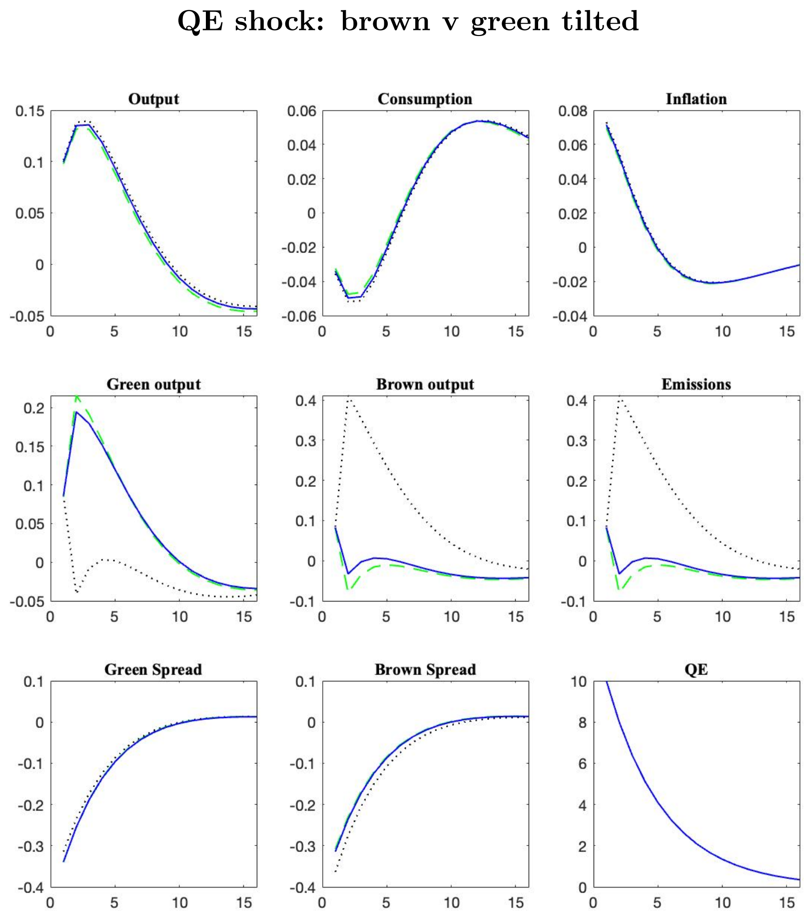


Figure 2: IRFs to a 10% positive QE shock: *Responses are in percent-deviations from steady state except for inflation and spreads whose response is in percentage point changes. The x axis shows time where one period is one quarter. Under the black dotted line, the composition of green and brown bonds in the central bank's balance sheet does not change i.e. the asset purchases are brown tilted. Under the green dashed line QE is entirely targeted to green bonds, and under the blue line QE is mostly targeted to green bonds.*

### 3.1.2 Capital Quality shock and QE response

Rather than being implemented in the above abstract way, QE is a response to adverse economic conditions. No existing paper, however, has fully considered how green QE could be used in crisis time. In this section, I implement a negative capital quality shock common to both sectors. This is intended as a simple approximation of financial crisis as in Gertler and Karadi (2011). I then consider a QE response to this shock by setting $\phi_\mu > 0$ so the central bank buys bonds when the credit spread increases.

Figure 3 shows a 5% capital quality shock which generates an increase in spreads and a decline in output, consumption and inflation under three scenarios. First, without any QE response (blue solid line), this is interpreted as a financial crisis. As output declines, emissions also fall below steady state. I then consider two QE responses, with the increase in bond holdings in each equivalent to 7% of the value of the

**Mid-size QE response to capital quality shock**

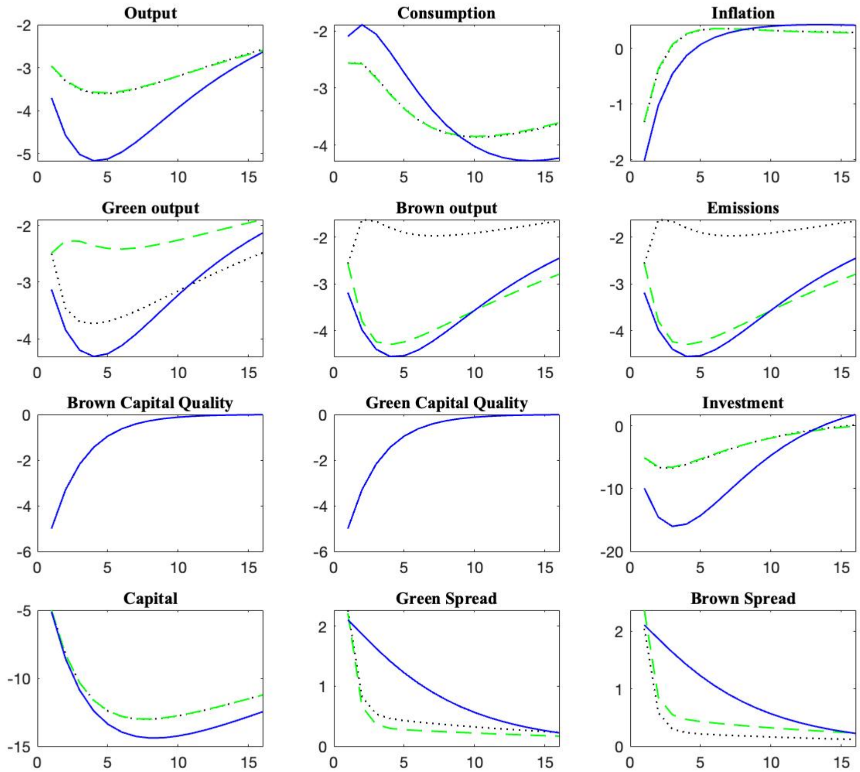


Figure 3: QE rule is set so the increase in size of CB bond holdings is 7% of the value of the capital stock: *Responses are in percent-deviations from steady state except for inflation and spreads whose response is in percentage point changes. Under the blue solid line, there is no QE response to the capital quality shock. Under the green dashed line the response is entirely targeted towards green bonds, and under the black dashed line the composition of bonds in the central bank's balance sheet does not change.*

capital stock as in Gertler and Karadi (2011) and Diluiso et al. (2021). Brown tilted QE as is implemented under the status quo is identified by the black dotted line. When QE is targeted entirely towards green bonds we get the response as shown by the green dashed line. The novel part of this shock relative to Gertler and Karadi (2011) is the response of green output, brown output, and emissions which is shown in the second line of the figure.

Green QE does just as well at stabilizing the economy as the brown QE - the path of output, consumption, inflation, capital, and investment are the same in both cases. However, the brown QE targets the emitting sector and therefore emissions are substantially higher in the brown case, though they are still below the steady state due to the output contraction caused by the capital quality shock. Figure 4 shows the same scenarios but here the increase in bonds held by the central bank is equivalent to 15% of the value of the capital stock. This is closer to the optimal increase in bond holdings found by Gertler and Karadi (2011). In this case, the response is large enough that emissions actually increase relative to

**Large QE response to capital quality shock**

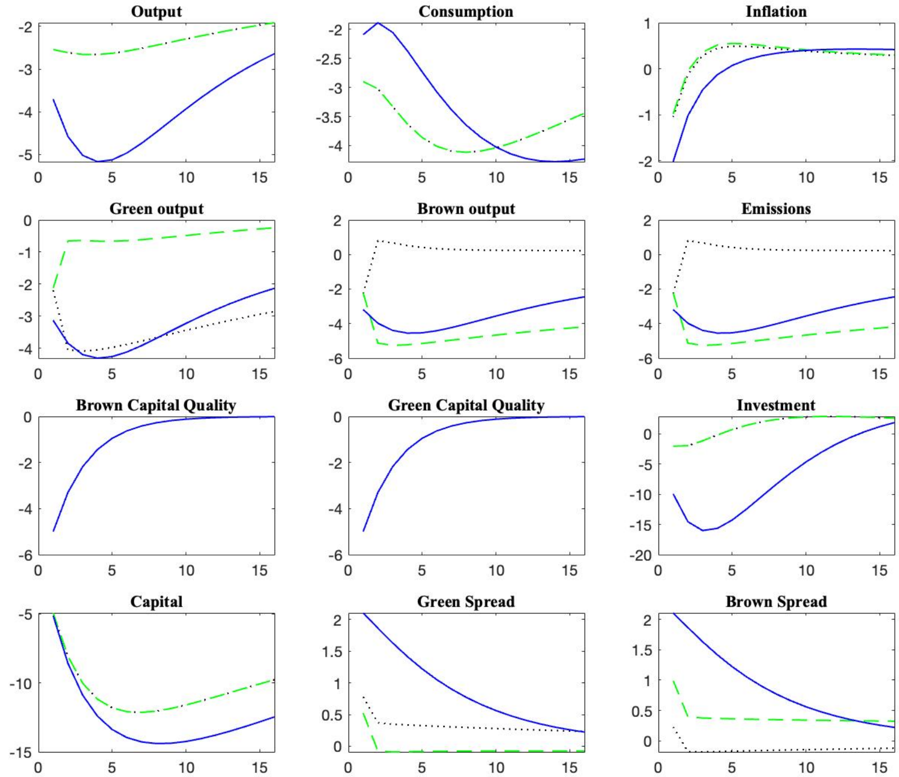


Figure 4: QE rule is set so the increase in size of CB bond holdings is 15% of the value of the capital stock: *Responses are in percent-deviations from steady state except for inflation and spreads whose response is in percentage point changes. Under the blue solid line, there is no QE response to the capital quality shock. Under the green dashed line the response is entirely targeted towards green bonds, and under the black dashed line the composition of bonds in the central bank's balance sheet does not change.*

the steady state when QE is brown tilted. This is of course undesirable - the financial crisis had the one benefit of reducing detrimental emissions, and the brown tilted QE needlessly reverses it.

The bottom line is that under the status quo ECB operationalization of the market neutrality principle, QE creates needless detrimental emissions. Green QE can achieve the same macro-stabilization outcomes as brown QE but without increasing emissions. This result is important as environmental mandates for central banks will be acceptable only if they do not interfere with their primary stabilization objectives. I have shown here that environmental and macro objectives can be reconciled.

### 3.1.3 QT

In the post-2020 world of high inflation, tight labour markets, and burdened central bank balance sheets, central banks are beginning to plan quantitative tightening - selling bonds in order to put upward pressure on the interest rate. The environmental implications of this are yet unexplored.

**QT shock**

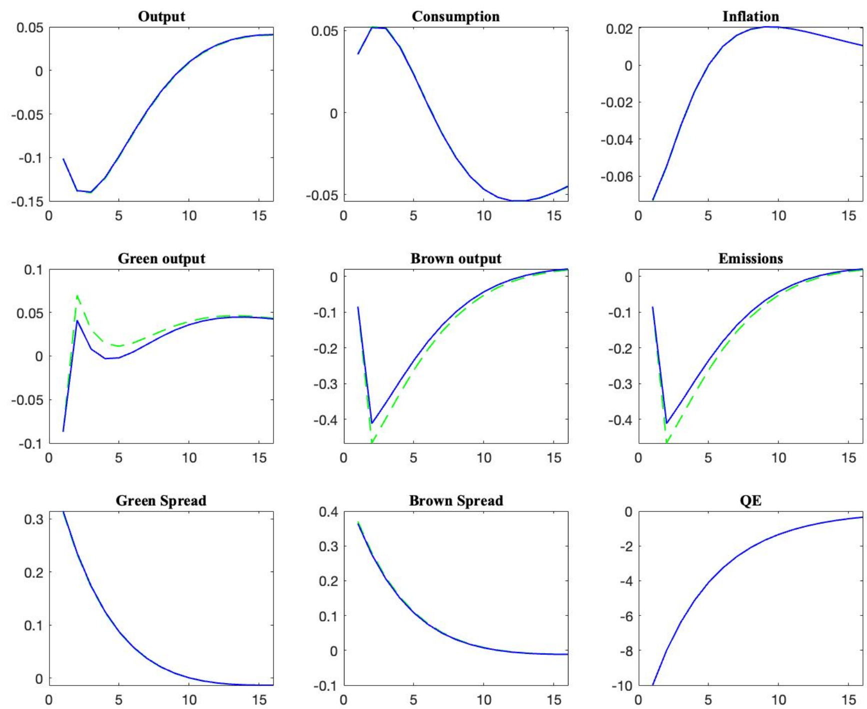


Figure 5: *Responses are in percent-deviations from steady state except for inflation and spreads whose response is in percentage point changes. Under the blue solid line, bonds are sold so as to keep the ECB composition the same i.e. more brown than green bonds are sold. Under the green dashed line, only brown bonds are sold.*

Figure 5 shows a temporary negative QE shock - or a QT shock. This 10% shock is the mirror image of the QE shock shown in Figure 2. Under the blue line $\mu^G$ remains constant i.e. more brown bonds than green are sold. Under the green dashed line, the ECB sells only brown bonds so the portfolio becomes more green i.e. $\mu^G$ increases. In both cases, selling relatively more brown bonds increases the brown interest rate relative to the green interest rate. Therefore, banks sell green and buy brown bonds. However, due to adjustment costs this doesn't fully counteract the effect of the ECB selling brown bonds and brown capital and output fall. As ECB holdings are tilted brown, selling bonds in proportion to existing holdings is desirable from a climate standpoint - it results in a decline in the brown sector and therefore a fall in emissions along with a boost to the green sector. Selling only brown bonds has the same aggregate macro effects and results in only slightly better emissions outcomes. If ECB holdings were in proportion to capital shares, selling bonds to keep the ECB portfolio composition the same would require selling more green bonds. This would result in a decline in the green sector, a smaller brown sector contraction, and a smaller fall in emissions. From this perspective, given that the ECB is more likely to engage in QT than in QE in the near future, the brown skew of the portfolio may actually be beneficial in terms of emissions.

### 3.2 Green QE as Climate Policy

The preceding section asks: how can central banks can minimize the environmental impact of QE once they decide to implement it? Here I consider whether green QE can be used as a lever of climate policy, i.e. can buying green bonds operate as an out of crisis-time policy to reduce emissions and boost green production? I consider non-expansionary green QE - an increase in the proportion of green ECB holdings achieved through selling brown and buying green bonds.

#### 3.2.1 Temporary Green QE shock

I first simulate a temporary shock to the green QE parameter $\mu^G$ where the size of the total ECB holdings $\mu$ is kept constant i.e. green bond purchases are completely financed by selling brown bonds. The shock is somewhat persistent but not permanent:

$$\frac{\mu_t^G}{\bar{\mu}^G} = \left(\frac{\mu_{t-1}^G}{\bar{\mu}^G}\right)^{\rho_G} \exp\left(v_t^{gqe}\right)$$

where $\rho_G = 0.8$. I consider two scenarios, in the first (solid blue line) the size of the shock is such that the ECB portfolio temporarily becomes ‘market neutral’ i.e. the proportion of green holdings increases from 0.33 to 0.65 in line with the size of the green sector. In the second (dashed green line), the size of the shock is set such that the ECB portfolio becomes heavily green tilted - i.e. 99% of ECB holdings are green.

The increase in green bonds held by the central bank reduces the interest rate paid by green firms meaning that the green spread decreases. As changing asset composition is costly, banks do not fully exploit the arbitrage opportunity. Therefore, there is a boost to green output and a decline in brown output. As brown output contracts, emissions also fall. The total amount of central bank bonds is kept constant and so output, consumption and inflation remain at steady state [17].

The size of the emissions reduction is substantial. Under the larger shock scenario there is a more than 3% decline in emissions on impact. This is comparable with the size of the emissions decrease resulting from a moderate increase in the carbon tax [18]. However, emissions quickly return to steady state by the nature of the temporary shock. This result is at odds with that presented in Ferrari, A. and Nispi Landi, V. (2020) where they claim that a temporary green QE shock only has small effects on environmental variables. This is because 1) they assume that the baseline is market neutral so only a 5% shock to $\mu^G$ is required to tilt the portfolio green, and 2) they use outdated atmospheric climate modelling. Further discussion of the climate modelling aspect follows in section 4.

#### 3.2.2 Permanent Green QE shock

The emissions response to the shock above is limited by its temporary nature - emissions come back to steady state as the central bank sells green bonds and buys brown bonds to bring its portfolio composition

[17] As capital shares $\alpha$ are equal across sectors, the fall in green output is compensated by an increase in brown output of the same size.

[18] See section 4 for details.

back to the (brown tilted) steady state. In order to fully consider the role green QE could play as climate policy, it would be useful to consider the effects of a permanent shift in the ECB's balance sheet towards green bonds. Ferrari, A. and Nispi Landi, V. (2020) claim that a permanent shock has no effect, even in the short run, when the device used to break the no-arbitrage condition is adjustment costs. When $\mu^G$ shifts to a new steady state, the steady state proportion of green bonds held by private banks also shifts to a new value of $b^*$. Therefore, banks immediately adjust their portfolios to avoid adjustment costs relative to this new steady state, $r^G = r^B$, and the green QE shock has no effect on real variables.

**Temporary Green QE shock**

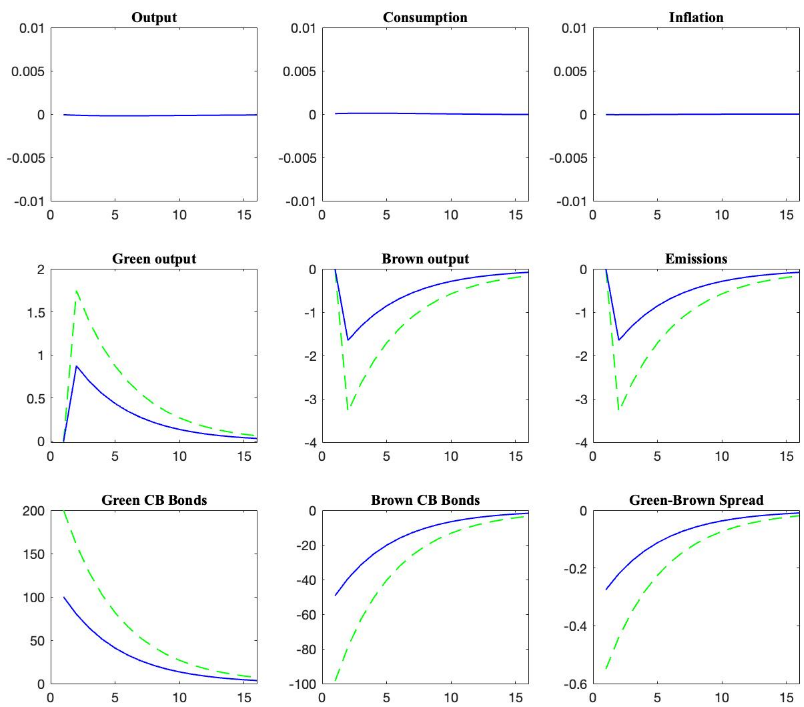


Figure 6: IRFs of a Green QE shock: *Responses are in percent deviations from steady state, except for the green-brown spread. Under the blue solid line the CB sells brown bonds to buy enough green bonds to bring it's portfolio composition in line with capital shares. Under the green dashed line the CB sells more brown bonds so that the porftolio becomes heavily green tilted.*

It seems reasonable to assume, however, that such adjustment would not be immediate and that there would at least be short run effects from the permanent shock. It could be the case that banks are unsure whether the shift in the central bank's portfolio towards green assets is temporary or permanent, and as such they may for a time pay adjustment costs around the original value of $b^*$. The central bank could choose to become more green without banks immediately following suit and adjusting their portfolios. Therefore, I run a permanent green QE shock with $b^*$ remaining at it's original level. The IRFs for this shock are given by figure 6 and the interpretation is that they show the *short run* effects of a permanent green QE shock before $b^*$ adjusts. Trivially, they show the same outcome as figure 5 but variables stabilize at their peak value and do not return to the original steady state. This means that emissions are depressed for longer and so the potential gain from the policy is higher. Another interpretation of this figure could be that of a *highly persistent* green QE shock rather than a permanent one. Over the time period considered, the IRFs of a very highly persistent shock are indistinguishable from those of a permanent shock (Appendix C).

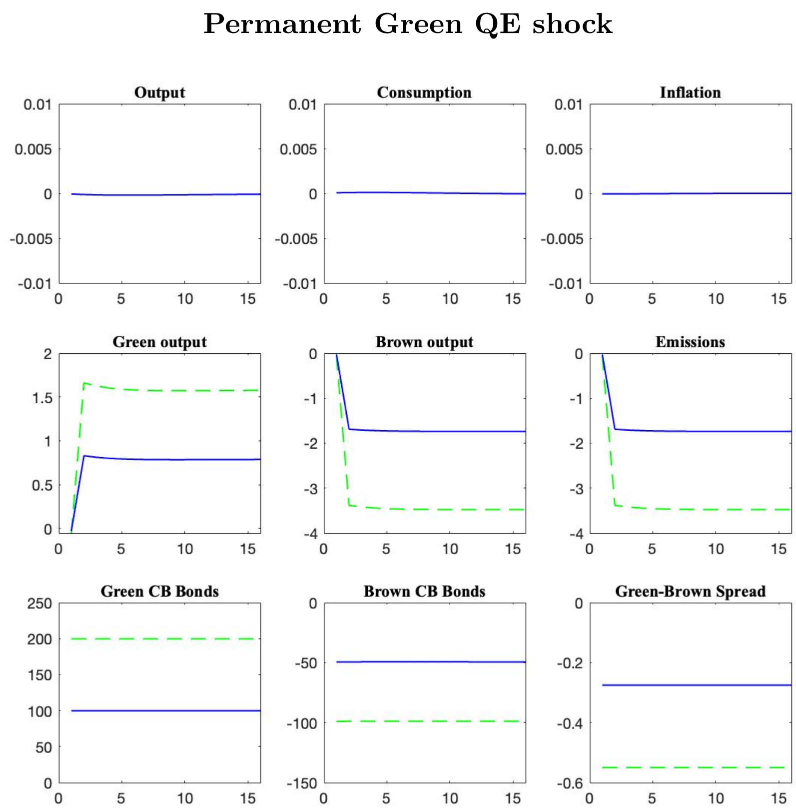


Figure 7: IRFs of a Green QE shock: *Responses are in percent deviations from steady state, except for the green-brown spread. Under the blue solid line the CB sells brown bonds to buy enough green bonds to bring it's portfolio composition in line with capital shares. Under the green dashed line the CB sells more brown bonds so that the porftolio becomes heavily green tilted.*

Eventually $b^*$ will adjust. Ferrari, A. and Nispi Landi, V. (2020) present one extreme where adjustment happens immediately, and I present another where it doesn't happen at all. An examination of the long run effects of the shock would require specifying a process for how $b^*$ adjusts. This is not trivial as there are multiple factors at play - if the central bank buys more green bonds this leaves less available for private banks, putting downward pressure on $b^*$, however green QE can stimulate increased bond issuance in the green sector thereby putting upward pressure on $b^*$. It has also been argued that green QE can have a signalling effect, inducing private banks to follow suit and buy more green bonds.[19] The conclusion

[19]Ferrari, A. and Nispi Landi, V. (2020) assume that the first effect is the only one and that $b^*$ immediately adjusts

here is that a permanent shift in the central bank's assets towards green bonds will lead to a substantial emissions decline, at least in the short run. I argue only that Green QE can have important environmental implications, not that it could be a substitute for a carbon tax [20].

### 3.3 Green QE and Transition Risk

Transition risks manifest when policies aimed at contributing to the shift to a low-carbon economy create instability in the macro-economy and/or financial sector. It has been shown that transition risk need not be a problem when the transition is 'orderly' i.e. when carbon prices are introduced at low levels and ratchet up over time in an expected way (Diluiso et al., 2021; NGFS, 2021b). However, if there are sudden policy changes, transition risk can become a problem. For example, a sharp unexpected increase in the carbon price can lead to brown asset stranding and bank equity losses. In the presence of financial frictions, a sudden increase in the carbon tax can lead to a contraction in the green sector as well as the brown sector - this is the 'green recession effect' (Carattini et al., 2021). Ideally, of course, a carbon tax would instead divert production from brown to the green sector. Here I consider whether a green QE rule can prevent this adverse green recession effect and as a result make carbon taxes more effective when they are implemented in sudden, disorderly scenarios which are increasingly relevant.

The model is modified to bring it in line with the literature which considers the worst case scenario risks of the transition. I model the extreme case as in Carattini et al. (2021) where capital is immobile and sector specific. This requires changing equations (A.23) and (A.24) into two separate equations each - one for green and one for brown capital. In order to prevent responses in labour to compensate for this capital immobility, I also make green and brown labour imperfectly substitutable: I modify the utility function so households choose both brown and green labour[21]:

$$N_t \equiv \left[ \left(N_t^B\right)^{1+\rho_L} + \left(N_t^G\right)^{1+\rho_L} \right]^{\frac{1}{1+\rho_L}}$$

where $\rho_L$ is set to 1 as in Horvath (2000).

Figure 8 shows the response of key variables to a sudden, unexpected increase in the carbon tax under two scenarios. In the first scenario (black dotted line), there is an increase in the tax of €15 per tone of carbon dioxide with out any QE response [22]. The carbon tax causes a sudden decline in brown output and a fall in the value of brown bonds. Therefore, bank net worth falls. As banks are balance sheet constrained, this results in a fall in lending to the green sector as well as the brown sector, and there is a drop in green output. As brown firms invest in abatement to reduce their tax liability, emissions fall by more than brown output. In the second scenario (green dashed line) the QE rule is switched on and targeted entirely towards green bonds i.e. there is an expansion in the amount of bonds owned by the central bank with the entire increase being made up of green bonds.

downwards. I assume that they roughly cancel out.

[20] It doesn't appear possible to get an emissions decrease big enough for long enough to make green QE a viable substitute for a carbon tax. For discussion of QE and carbon taxes in tandem see Ferrari and Nispi Landi (2022) and Ariby et al. (2022)

[21] Green and brown labour being imperfect substitutes is arguably a reasonable assumption, at least in the short run - a hospitality sector worker can't immediately become an agricultural worker as the skills required are different.

[22] The €15 figure is chosen for illustrative purposes. It brings the EUETS price up to around €100.

**Carbon Tax and QE response**

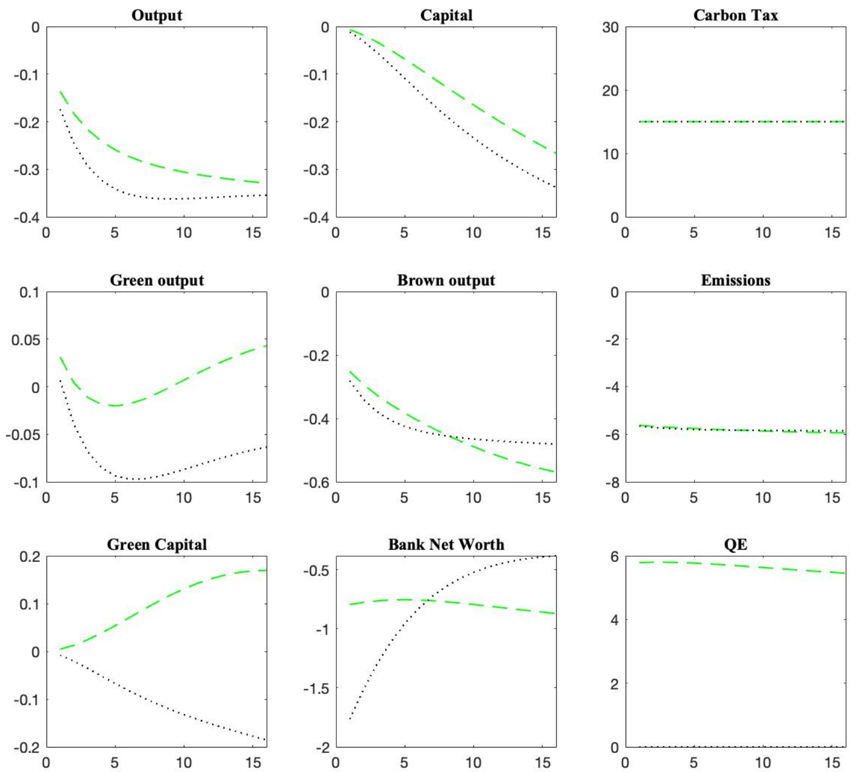


Figure 8: *Responses are in percent deviations from steady state, except for the carbon tax which shows increase in euros above steady state. Under the black dotted line there is a sudden unexpected carbon tax shock. Under the green dashed line the QE rule is turned on and targeted entirely towards green bonds.*

The green QE response almost entirely counteracts the initial dip in green output, and creates a green expansion in later periods. As a result, the output and capital declines are also somewhat reduced. This is achieved without undermining the function of the carbon tax - brown output still falls as do emissions. A green QE rule can work to prevent a green recession arising from the sudden introduction of ambitious climate policy. This is important as adverse effects of carbon taxes on the economy have been cited as reasons not to implement them and so could open the door for more ambitious climate policy. This result could be more relevant to countries without a carbon tax at all where sudden increases may be required in the coming years [23]. The cost of this intervention is the increase in the size of the central bank balance sheet but this increase is relatively small - the proportion of bonds held by the central bank increases to around 0.106 from 0.1.

The assumption that capital is immobile across sectors is a relatively strong one. A similar result could be achieved by assuming that there was some adjustment cost to be paid when converting green to brown capital or vice versa, though the effect would be quantitatively smaller. If capital is fully mobile as it is in

[23] In the case of countries without an existing carbon tax, the shock required may be larger. The green recession effect is increasing in the size of the carbon tax shock, making a green QE rule even more relevant in these cases.

the baseline model, the sudden introduction of the carbon tax does not result in the green recession effect. The point of this section is to show that if there is a green recession effect due to capital frictions, green QE can alleviate it. The simulations are repeated with mobile capital and labour in Appendix C.

### 3.4 Sensitivity

The results presented above are sensitive to a number of the model parameters. As noted above, imperfect substitutability between green and brown bonds is necessary for green QE to affect environmental variables. As long as the key parameter $\kappa_{FG} > 0$, the qualitative results presented in section 3 hold. However the size of the emissions response depends crucially on the size of $\kappa_{FG}$. Figure 1 in Appendix C illustrates this - the emissions response is larger when brown and green bonds are less close substitutes. This is the key result of Ferrari, A. and Nispi Landi, V. (2020).

As noted in section 2, I set the baseline elasticity of substitution between green and brown inputs to 1. However, there is disagreement in the literature as to what this elasticity actually is. I therefore present the simulation from figure 6 for three values of this elasticity: 0.5, 1, and 2 in Appendix C. The more substitutable green and brown inputs are, the bigger the response to green QE. However, the quantitative difference is small, and in all cases the qualitative results presented in section 3 hold.

Following Ferrari, A. and Nispi Landi, V. (2020) I set the size of steady state QE, $\mu$, to 0.1. However, if the ECB holds a higher proportion of bonds, as it does according to Papoutsi et al. (2021), bringing the portfolio in line with capital shares requires selling more brown and buying more green bonds. Therefore, the effect of a green QE shock on brown output and emissions is larger. Figure 3 in Appendix C illustrates this effect. The persistence of the QE shock is also important for the size of the effect on cumulative emissions. Figure 4 in Appendix C shows that the more persistent the shock is, the bigger the decline in cumulative emissions is.

## 4 Normative Analysis

The climate module is used to quantify the size of the environmental gain from implementing green QE. These calculations should be taken with a pinch of salt as the size of the emissions gain from greening QE depends on the parameter $\kappa_{FG}$. The main result is a qualitative one - green QE can achieve the same macro outcomes as brown QE with less emissions, and tilting the ECB portfolio towards green bonds can reduce emissions at least in the short run. However, I take this opportunity to say something about the potential size of this gain given the baseline value of $\kappa_{FG}$. The size of the benefit from switching to green QE outlined here is larger than that claimed by Ferrari, A. and Nispi Landi, V. (2020) due in part to the more physically accurate climate modelling.

There are two main problems with the approach to modelling climate-economy interactions utilized by much of the business cycle literature on climate policy. First, the process specified to link periodic emissions to atmospheric carbon is physically inaccurate as it abstracts from the permanent part of the stock of carbon. There should be one unit root in the atmospheric carbon process but this is left out (Joos et al., 2013; Geoffroy et al., 2013). In these models the delay between emissions and peak warming is much too long, resulting in carbon prices which are too low, and an inflated importance of the discount rate (Dietz et al., 2021; Dietz and Venmans, 2019). Secondly, the specification and calibration of the damage function which links atmospheric carbon to TFP is deeply contentious. Substantial uncertainties over economic damages and loss of human lives at higher temperatures mean that specifying a damage function is often not much more rigorous than a guessing game, with significant disagreement over the correct functional form and calibration. Models which rely on damage functions often result in recommendations on climate policy which are far out of step from the scientific consensus on 'optimal warming' and costs v 'benefits' of climate change (Weitzman, 2012; Pindyck, 2021; Casey et al., 2022). Full climate science models of warming are large and difficult to integrate into a conventional DSGE model. Fortunately, these complicated dynamics can be summarized by a system of two equations which shows the robust scientific relationship between cumulative emissions and temperature - equations 35 and 36. [24]. Updating integrated assessment models with these climate dynamics has improved their performance and brought them closer to climate science models (Dietz et al., 2021).

Here I choose not include a damage function due to the lack of a robust foundation. Under the most common damage function specifications, damages are small over the time period considered anyway, so disregarding them does not affect the results. This has the added benefit that temperature does not feed back into the economic model and so the unit root in the cumulative emissions process is not a problem. Given that the response of consumption to a green QE is the same as to a comparable brown QE in all of the results presented here, the preferable policy in terms of welfare is that which results in better environmental outcomes. Therefore, normative analysis is conducted after the policy simulations, rather than through maximizing welfare taking damages into account. I use the cumulative emissions - temperature relationship to evaluate the gains from green QE in two ways: 1) effect on temperature, 2) monetary value of emissions avoided, calculated using the carbon price.

The table presents the relevant information. The first two columns show the cumulative emissions created by engaging in brown tilted rather than green tilted QE i.e. the simulations considered in section 3.1, the emissions avoided by selling brown and buying green bonds i.e. the simulations from section 3.2, and the emissions reduction caused by a €10 increase in the carbon tax. The increase in cumulative emissions from brown QE relative to green QE is substantial - creating up to 0.2422 gigatonnes of additional carbon dioxide over four years. A shift in the ECB portfolio towards green bonds can also create substantial emissions declines - the largest case shown here of a highly persistent 200% green QE shock leads to an emissions decline comparable to that of a €10 increase in the carbon price.

The next two columns show temperature effects for the likely range of TCRE values laid out by the IPCC. As the EA is responsible only for a small share of global emissions, the effect of Brown v Green QE on global average surface temperature is of course small assuming that rest of world emissions remains unaffected. The largest effect is from the persistent green QE shock which creates a strong green tilt in the ECB's portfolio. This results in a temperature decrease which is also small but comparable with the decrease achieved by an increase in the carbon price of €10.

[24]The linear relationship between cumulative emissions and temperature has been shown to be roughly constant over time (IPCC, 2021)

| **Shock** | **Cuml. Emissions** | | **Temperature** | | **Monetary Value** | |
|---|---|---|---|---|---|---|
| | 1 year | 4 years | $\iota = 0.001$ | $\iota = .0023$ | €bn | %GDP |
| 10% QE shock | 0.0102 | 0.013 | 0.000013 | 0.00003 | -1.157 | -0.0089 |
| Mid-size response to CQS | 0.033 | 0.148 | 0.000148 | 0.00034 | -13.172 | -0.1013 |
| Large response to CQS | 0.0685 | 0.2442 | 0.0002442 | 0.00056 | -21.734 | -0.167 |
| Temp GQE shock to market neutral | -0.0248 | -0.0448 | -0.0000448 | -0.0001 | 3.901 | 0.031 |
| Perm GQE shock to market neutral | -0.0333 | -0.1383 | -0.0001383 | -0.000318 | 12.311 | 0.095 |
| Temp GQE shock to green tilt | -0.0497 | -0.0895 | -0.0000895 | -0.00021 | 7.9655 | 0.061 |
| Perm GQE shock to green tilt | -0.0666 | -0.2766 | -0.0002766 | -0.000636 | 24.617 | 0.189 |
| €10 increase in $\tau^F$ | -0.0677 | -0.2786 | -0.002786 | -0.00064 | 24.795 | 0.191 |

Table 1: **Climate Effects of QE:** *Cumulative emissions are in gigatonnes of carbon dioxide. The first three rows show the increase in cumulative emissions from brown compared to green QE. The following four rows show the emissions avoided by engaging in green QE. Temperature effects are shown in degrees Celsius.*

The penultimate column shows the monetary value of implementing green rather than brown QE in terms of the emissions created or avoided, calculated using the current value of the EU ETS carbon price.[25] I also express this figure as a percentage of EA GDP[26]. There is a substantial cost in terms of emissions created from brown QE - up to almost €22bn. Given that green QE can achieve the same macro-stabilization outcomes as brown QE, then, the case for green QE is strong. Similarly, the value of the emissions avoided when a green QE shock is implemented is substantial. As the carbon price increases over time, the cost of brown relative to green QE will also increase, making the case for greening QE stronger. Moreover, given that climate policy is increasingly being made on the basis of 'emissions budgets', the emissions needlessly created by brown QE would have knock on effects in terms of emissions reductions which would have to be made elsewhere to keep emissions below budget. As time goes on and emissions budgets decrease/ carbon prices increase, the costs of engaging in brown QE too will increase.

# 5 Conclusion

This paper contributes to the literature on the potential for a climate mandate for central banks, considering the case of green QE. Green QE can be a useful policy lever and effectively target environmental variables in certain settings. Crisis time green QE achieves the same macro-stabilization outcomes as status quo brown tilted QE without the detrimental emissions. This indicates that an environmental mandate can be reconciled with central banks' primary price and output stabilization mandates. As green QE avoids the emissions increase created by brown QE, its outcomes are preferable in terms of welfare. Green QE is therefore consistent with the idea of 'never wasting a crisis' - the recovery from a financial crisis is accompanied by a recovery policy which also works towards the green transition.

[25] €88 in May 2022.

[26] I set EA GDP to 13,000bn euro based on IMF data.

Outside of crisis time, selling brown and buying green bonds can achieve substantial emissions reductions, at least in the short run. Though the emissions decrease achievable is not large enough to make green QE a realistic substitute for more direct climate policy e.g. a carbon tax, it could free up space in tight emissions budgets. Given that the current operationalization of the market neutrality principle leads to a strong brown tilt in the ECB portfolio, this has the implication that the ECB should bring its portfolio in line with market shares. This could be achieved either within the framework of market neutrality but defined relative to market shares rather than outstanding bonds, or by going beyond market neutrality and accepting a more active environmental mandate. Finally, a green QE rule can prevent a contraction in the green sector when carbon taxes unexpectedly increase, without compromising on the emissions goals of that tax. This is likely to be useful in the future as government delays on climate policy make future drastic carbon price shocks more necessary and probable.

A number of limitations present opportunities for future work. First, the friction which introduces adjustments costs for banks reallocating their portfolios is not micro-founded and there are no good empirical estimates of the key parameter $\kappa_{FG}$. Consequently, it is difficult to be precise about the size of the effect of a green QE shock on macro and environmental variables. Future research could exploit bank level data to develop an empirical estimate of the extent to which green and brown bonds are imperfect substitutes. Second, there is a need for further work on the long run effects of a permanent green tilt in the central bank portfolio. A credible approach to this question would give attention to the ideas of central bank moral suasion or signalling when purchasing green bonds. Thirdly, and relatedly, it would be useful to consider the effects that green QE could have on debt issuance and longer term investments. It has been argued that brown QE can encourage brown investment and lead to carbon lock in, and that a green QE could instead finance investment in green technologies. The model presented here does not capture carbon lock in effects - an extension which incorporates path dependence of investments and longer term bonds would be better placed to consider this.

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