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TOWARD A GREEN ECONOMY: THE ROLE OF CENTRAL BANK'S ASSET PURCHASES

by Alessandro Ferrari* and Valerio Nispi Landi*

Abstract

We use a DSGE model to study the effectiveness of a Green QE, i.e. a program of green-asset purchases by the central bank, along the transition to a carbon-free economy. The model is characterized by green firms that produce using a clean technology that does not pollute and brown firms that pollute but can pay an abatement cost to reduce emissions. The transition is driven by an emission tax. We analyze the evolution of macroeconomic variables along the transition and we compare different versions of Green QE. Two main findings emerge from our baseline calibration, where the green good and the brown good are imperfect substitutes. First, Green QE helps to further reduce emissions along the transition, but its quantitative impact on the stock of pollution is small. Second, we find the largest effects when the central bank invests in green assets in the early stage of the transition. Moreover, we highlight that if the green good and the brown good are imperfect complements, Green QE *raises* emissions.

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1 Introduction[1]

Limiting the escalation in global temperature is one of the big challenges of the 21^{th} century. According to the scientific community, the acceleration of temperature increase observed in the last decades is largely driven by an exponential rise in greenhouse gas emissions, as a result of the expansion in global production since the industrial revolution. As of November 2021, almost all countries in the world had ratified the Paris Agreement, which has the ambitious goal of keeping a global temperature rise throughout the current century well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the rise to 1.5 degrees. In order to meet these goals, the European Union aims to be climate-neutral by 2050, by reaching net-zero greenhouse gas emissions.

Designing effective environmental policies is a task for elected governments, which have the most appropriate instruments to address the climate challenge. Several economists have been suggesting that also central banks may play a role to mitigate the increase in global temperature: according to De Grauwe (2019), Schoenmaker (2019), Brunnermeier and Landau (2020), one option on the table is to design a program of green asset purchases, the so called "Green QE". Central banks such as the ECB, the Bank of England, and the Sverige Riksbank have indeed started to study how to decarbonize their balance sheets and in particular their monetary policy portfolios.

Motivated by these facts, we ask whether Green QE is useful in further reducing the flow of emissions and the stock of atmospheric carbon along the transition.[2] We answer this question through the lenses of a DSGE model, calibrated on the euro area. We define Green QE as a purchase program of green bonds by the central bank, financed with higher reserves. The model features two production sectors: a green sector, where firms do not pollute; a brown sector, where production generates CO2 emissions, which fuel the stock of atmospheric carbon. Brown firms are charged with a tax per unit of emissions; in order to reduce tax payments, brown firms can cut emissions by increasing abatement spending. We model the attention paid by households to the environmental content of their investments by assuming that they enjoy utility from investing in green bonds and suffer disutility from investing in brown bonds. This assumption captures the taste for specific types of assets along the lines of Fama and French (2007) and it is consistent with the existence of a negative premium between green and brown bonds, the so called "greenium" (as in Zerbib, 2019, Fatica et al., 2021, and Liberati and Marinelli,

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[1] We thank our discussant Ivan Jaccard for his useful feedback. We are also grateful to Alessandro Cantelmo, Stefano Neri, Francesco Paternò, Alessandro Secchi, Andrea Tiseno, and seminar online participants at the 5th Workshop of the ESCB Research Cluster on Monetary Economics for their comments and suggestions. The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the Bank of Italy.

[2] In the paper we use the terms "atmospheric carbon" and "pollution" interchangeably.

2021). Crucially, this assumption breaks the Wallace neutrality (Wallace, 1981), making green and brown bonds imperfect substitutes for households in the short and in the long run: if the central bank purchases green bonds by issuing reserves the greenium becomes even more negative.

We carry out the following two experiments.

First, we simulate the transition to an emission-free economy. The government sets an emission tax that increases over time for 30 years, in line with the European Commission environmental targets, up to the point that brown firms fully abate emissions. By increasing production costs for the brown sector along the transition, resources shift from the brown to the green sector, which becomes bigger in relative terms in the new steady state. We show that in the new steady state consumption falls by around 10%, compared to a scenario with no emission taxes: however, we are somewhat over-estimating the consumption reduction, because in our model pollution does not affect total factor productivity.[3]

Second, we simulate three different types of Green QE by the central bank along the transition, on top of the government's emission-tax policy. We model Green QE as an additional envelope of purchases by the central bank targeted only to green bonds. The expansion of the balance sheet is financed by issuing reserves. The three types of Green QE differ as to the timing of the purchases and the persistence of the policy: i) gradually increasing and permanent; ii) front loaded and permanent, i.e. the central bank commits to keep an additional envelope of green bonds forever in its balance sheet; iii) front-loaded and transitory, i.e. the central bank allows the stock of green bonds held to decline after some years. We show that Green QE is more effective in reducing the stock of pollution when purchases are concentrated in the first years of the transition (cases ii and iii), where the link between emission and brown production is still not weakened by abatement spending. Instead, the effect on pollution is much smaller, when Green QE increases gradually (case i) because the bulk of purchases takes place at the end of the transition when high abatement spending weakens the link between emissions and brown production. However, from a quantitative point of view, the effect on the stock of pollution, either global and European, is very small in every scenarios.

We also identify some parameters that are important for the effectiveness of Green QE along the transition. First, the highest the curvature of the bond utility function the more Green QE is effective, as in this case households change by less their asset composition, weakening the Wallace neutrality principle. Second, when the green and the brown goods are complements, we find that Green QE *increases* emissions: in this case the resulting expansion of green output implies a *larger* demand of brown good,

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[3] Making TFP dependent on pollution would not allow to solve for a balanced growth path.

brown production rises, and so emissions. Third, we show that the effectiveness of Green QE is convex in the size of purchases. Finally, a lower steady-state greenium reduces the relevance of the bond utility function, strengthening the Wallace neutrality principle and making green QE less effective.

Our paper fits in the stream of the literature that studies the transition to a carbon-free economy in general equilibrium models. William Nordhaus simulates the long-run effects of climate change studying different policy scenarios in several applications of his DICE model (Nordhaus, 2008, Nordhaus and Sztorc, 2013, Nordhaus, 2017). Diluiso et al. (2021) analyse financial and monetary policies along the transition to an economy with lower emissions and in response to negative shocks in the brown sector. Benmir and Roman (2020) study monetary and macroprudential policies that can attenuate the welfare losses driven by the introduction of a carbon tax. Carattini et al. (2021) assess the financial risk arising from climate policies and how it can be mitigated through macroprudential policy. Bartocci et al. (2021) introduce green subsidies and carbon taxes in a large-scale model, studying several policies. In a two-country model, Ferrari and Pagliari (2021) find that conventional monetary policy displays little effects in reducing emissions along the green transition, but it could partially shield households from the cost of the brown tax. With respect to these papers, we analyse the role of Green QE along the transition: we show that Green QE helps reducing emissions, but the impact on the stock of global and European pollution is small.

In a previous paper (Ferrari and Nispi Landi, 2021), we study the effects of a transitory Green QE that cannot have any effect in steady state; in the present paper we also consider a permanent Green QE that can be effective in the long run, and we analyse the effect of purchase programmes along the transition to an economy with zero emissions. This is possible as in the model used in this paper green and brown bonds are explicitly included in the households' utility function, making green and brown bonds imperfect substitutes also in the long run; in our previous paper we make the two bonds imperfect substitutes only in the short run, by modelling transitory transaction costs in the financial sector.

2 Model

We set up a New Keynesian framework augmented with a green and a brown sector, as in Ferrari and Nispi Landi (2021). The green sector produces the green output, and it does not pollute. The brown sector produces the brown output and it generates emissions. The flow of emissions fuels the stock of atmospheric carbon. Brown firms decide how much to spend in abatement to limit emissions and thus to reduce carbon-tax spending. The green and the brown outputs are used as inputs by a continuum of intermediate firms, that act in monopolistic competition and are subject to nominal rigidities. A final good-firm combines the differentiated intermediate goods to produce a final good. The final good is bought by households for consumption and by capital producers, which transform it in physical capital.

The main goal of the paper is not a welfare evaluation of Green QE: for simplicity, unlike most of the literature, in this model pollution is not detrimental for total factor productivity. This assumption allows to easily find a balance growth path of the model, with most variables that grow along this path at the exogenous growth rate of the labor augmenting productivity.[4] The goal of this paper is a positive analysis of Green QE along the transition to a zero-emission economy: in the model, the transition is not necessarily optimal, and we take it as given.

From now on we denote with G the green sector and with B the brown sector. We indicate with a "tilde" variables that are detrended, i.e. that are divided by the non-stationary labor-augmenting productivity z_t; we indicate with a "hat" detrended variables in percentage deviations from the steady state; variables without a time index are meant to be in steady state.

In what follows, we lay out the optimization problems of all the agents of the model. We leave the full list of equations to the Appendix.

2.1 Households

The representative household maximizes the following utility function:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log c_t - \frac{h_t^{1+\varphi}}{1+\varphi} + \frac{1}{z_t} \left[\frac{\nu_G}{1-\kappa_G} \left(\frac{B_{Ht}^G}{P_t z_t} \right)^{1-\kappa_G} - \frac{\nu_B}{1+\kappa_B} \left(\frac{B_{Ht}^B}{P_t z_t} \right)^{1+\kappa_B} \right] \right\},$$

subject to the budget constraint:

$$c_t + \frac{D_{Ht} + B_{Ht}^G + B_{Ht}^B}{P_t} = \frac{r_{t-1} D_{Ht-1} + R_t^G B_{Ht-1}^G + R_t^B B_{Ht-1}^B}{P_t} + w_t h_t - t_t + \Gamma_t. \tag{1}$$

The choice variables are consumption c_t, hours worked h_t, the nominal holding of green and brown one-period bonds B_{Ht}^G and B_{Ht}^B, and the nominal holding D_{Ht} of one-period public bonds plus central bank's reserves;[5] R_t^G, R_t^B, and r_t are the nominal interest rate on green, brown, and public bonds respectively; w_t is the hourly wage; t_t denotes lump-sum taxes; Γ_t denotes profits from ownership of firms; P_t is the CPI level; z_t is labor-augmenting TFP, which grows at rate θ.

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[4] We could assume that pollution yields disutility to households. As far as pollution enters "separable" in the utility function, our results would not change.

[5] Public bonds and reserves are perfect substitutes and pay the same interest rate r_t.

Green bonds are issued by firms that do not pollute, while brown bonds are issued by firms that generate detrimental emissions. We are assuming that utility is increasing in the amount of real detrended green bonds, and decreasing in the amount of real detrended brown bonds.[6] With this assumption we aim to capture the taste of investors for specific assets beyond the payoffs, in the spirit of Fama and French (2007) and Hartzmark and Sussman (2019). It turns out that green and brown bonds are not perfect substitutes, and in equilibrium a negative green-brown spread opens up: our model features the so called "greenium", in line with several studies (Zerbib, 2019, Fatica et al., 2021, and Liberati and Marinelli, 2021). This assumption also ensures that Wallace neutrality does not hold and Green QE is effective.[7] When the central bank buys green bonds, households require a higher premium on brown bonds, given their preference for green investments: the interest rate on brown bonds goes up, and brown firms issue less bonds. Unlike Ferrari and Nispi Landi (2021), the Wallace neutrality does not hold in the long-run neither, making Green QE effective also in the long run.[8]

Define the following real variables: $d_t \equiv \frac{D_t}{P_t}$, $b^G_{Ht} \equiv \frac{B^G_{Ht}}{P_t}$, $b^B_{Ht} \equiv \frac{B^B_{Ht}}{P_t}$, $r^G_t \equiv \frac{R^G_t}{\pi_t}$, $r^B_t \equiv \frac{R^B_t}{\pi_t}$, where π_t is the gross inflation rate. The first order conditions of the problem yield the following Euler equations:

$$
\begin{aligned}
1 &= \beta \mathbb{E}_t \left(\frac{c_t}{c_{t+1}} \frac{r_t}{\pi_{t+1}} \right) && (2) \\
1 &= \beta \mathbb{E}_t \left(\frac{c_t}{c_{t+1}} r^G_{t+1} \right) + \frac{\nu_G c_t}{z_t} \left(\frac{b^G_{Ht}}{z_t} \right)^{-\kappa_G} && (3) \\
1 &= \beta \mathbb{E}_t \left(\frac{c_t}{c_{t+1}} r^B_{t+1} \right) - \frac{\nu_B c_t}{z_t} \left(\frac{b^B_{Ht}}{z_t} \right)^{\kappa_B}, && (4)
\end{aligned}
$$

and an expression for the labor supply:

$$
c_t h_t^{\varphi} = w_t. \qquad (5)
$$

Linearizing equations (3) and (4) around a steady state with constant productivity

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[6] We pre-multiply bond utility by labor-augmenting TFP z_t in order to get a balance-growth path.

[7] Assets in the utility function is a common assumption in the DSGE literature. Recently, macroeconomists have used this assumption to make bonds imperfect substitutes thus breaking the Wallace neutrality (Alpanda and Kabaca, 2020), to better explain the data (Rannenberg, 2021) and to solve several puzzles of New Keynesian models (Michaillat and Saez, 2021).

[8] Both green-bond utility and brown-bond disutility are necessary for the effectiveness of Green QE in the long run. Having only green-bond utility would make brown and public bonds perfect substitutes: the brown rate would be equal to the real policy rate, which in steady state does not depend on central's bank policy. Having only brown-bond disutility would make green and public bonds perfect substitutes: any increase in green bond holding by the central bank would be offset by a sale of green bonds by households.

growth, we get the following arbitrage conditions:

$$\hat{b}^G_{Ht} - \hat{b}^B_{Ht} = \eta \mathbb{E}_t \left(\hat{r}^G_{t+1} - \hat{r}^B_{t+1} \right) + 2\hat{c}_t, \tag{6}$$

where we impose $\eta \equiv \frac{r^B}{\kappa_B (r^B - rr)} = \frac{r^G}{\kappa_G (rr - r^G)}$, and rr is the real interest rate on public bonds in steady state. The previous condition shows that a reduction in the green-brown spread induces households to replace green with brown bonds, other things equal: if bonds did not enter the utility function, $\eta \to \infty$, and the spread would be always 0.

2.2 Final-good firms

The representative final-good firm uses the following CES bundle to produce the final good y_t:

$$y_t = \left[\int_0^1 y_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{7}$$

where $y_t\left(i\right)$ is an intermediate good produced by intermediate firm i, whose price is $P_t\left(i\right)$. The profit maximization problem yields the following demand function $\forall i$:

$$y_t(i) = y_t \left(\frac{P_t(i)}{P_t} \right)^{-\varepsilon}. \tag{8}$$

2.3 Intermediate-good firms

There is a continuum of firms indexed by i, producing a differentiated input and using the following function:

$$y_t\left(i\right) = y^I_t\left(i\right), \tag{9}$$

where y^I_t is a CES bundle of green production y^G_t and brown production y^B_t:

$$y^I_t\left(i\right) = \left[(1-\zeta)^{\frac{1}{\xi}} \left(y^G_t\left(i\right) \right)^{\frac{\xi-1}{\xi}} + \zeta^{\frac{1}{\xi}} \left(y^B_t\left(i\right) \right)^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}. \tag{10}$$

Firms operate in monopolistic competition and they set prices subject to the demand of the final-good firm (8). Firms pay quadratic adjustment costs $AC_t\left(i\right)$ in nominal terms:

$$AC_t\left(i\right) = \frac{\kappa_P}{2} \left(\frac{P_t\left(i\right)}{P_{t-1}\left(i\right)} - \overline{\pi} \right)^2 P_t y_t,$$

where $\overline{\pi}$ is the inflation target.

The intermediate firm i solves an intratemporal problem to choose the optimal input combination, and an intertemporal problem to set the price. The intratemporal problem, i.e. minimizing costs subject to a given level of production, reads:

$$\min_{y_t^B(i), y_t^G(i)} p_t^G y_t^G(i) + p_t^B y_t^B(i)$$

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

where p_t^G and p_t^B are the price of green and brown production respectively, expressed relatively to the CPI. The problem yields the following demand functions for the green and brown input:

$$y_t^G(i) = (1-\zeta)\left(\frac{p_t^G}{p_t^I}\right)^{-\xi} y_t^I(i) \tag{11}$$

$$y_t^B(i) = \zeta\left(\frac{p_t^B}{p_t^I}\right)^{-\xi} y_t^I(i), \tag{12}$$

where $p_t^I = \left[(1-\zeta)\left(p_t^G\right)^{1-\xi} + \zeta\left(p_t^B\right)^{1-\xi}\right]^{\frac{1}{1-\xi}}$ is the real marginal cost of the firm.

The intertemporal problem reads:

$$\max_{\{P_t(i)\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{\sum_{t=0}^{\infty} \beta^t \frac{c_0}{c_t}\left[\left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon}\left(\frac{P_t(i)}{P_t} - p_t^I\right) y_t - \frac{\kappa_P}{2}\left(\frac{P_t(i)}{P_{t-1}(i)} - \overline{\pi}\right)^2 y_t\right]\right\},$$

where firms use the same stochastic discount factor of households. In a symmetric equilibrium, the intertemporal problem yields a non-linear Phillips Curve:

$$\pi_t\left(\pi_t - \overline{\pi}\right) = \beta\mathbb{E}_t\left[\frac{c_t}{c_{t+1}}\pi_{t+1}\left(\pi_{t+1} - \overline{\pi}\right)\frac{y_{t+1}}{y_t}\right] + \frac{\varepsilon}{\kappa_P}\left(p_t^I - \frac{\varepsilon-1}{\varepsilon}\right), \tag{13}$$

which links inflation to real marginal costs. If $\kappa_P > 0$, changing prices is costly and the classical dichotomy between nominal and real variables is broken.

2.4 Green and brown firms

Green and brown firms use the following production function, for $j = G, B$:

$$y_t^j = \left(k_{t-1}^j\right)^{\alpha}\left(z_t h_t^j\right)^{1-\alpha}, \tag{14}$$

where k_t^j and h_t^j are capital and labor used in sector j. Green and brown firms issue bonds b_t^j to households and to the central bank. Bonds finance capital expenditure:

$$b_t^j = q_t k_t^j, \tag{15}$$

where q_t is the price of the capital good. The bond is expressed in real terms and pay a real interest rate r_t^j, for $j = G, B$. Firms buy capital from capital producers, which in turn buy back non-depreciated capital from basic firms; hence, the effective cost of capital for brown firms reads

$$r_{kt}^B \equiv r_t^B q_{t-1} - (1-\delta)\, q_t, \tag{16}$$

where δ is the depreciation rate of capital.

Firms pay a tax τ_t for unit of emissions e_t. The tax is relevant only for brown firms, as green firms do not pollute; as in Nordhaus (2008), we assume that for each unit of brown output, brown firms release $\nu_E\,(1-\mu_t)$ carbon-model units in the atmosphere, as shown by the following emission function:

$$e_t = \nu_E\,(1-\mu_t)\, y_t^B, \tag{17}$$

where μ_t is the fraction of emissions that brown firms abate. The flow of emissions fuels the stock of atmospheric carbon x_t:

$$x_t = (1-\delta^x)\, x_{t-1} + e_t + e_t^{row}, \tag{18}$$

where e_t^{row} denote exogenous rest-of-the-world emissions, which grow at the same rate of labor-augmenting productivity z_t. Following Nordhaus (2008), we assume a convex abatement-cost function ABC_t:

$$ABC_t = \frac{\nu_M}{1+\chi}\mu_t^{1+\chi} y_t^B. \tag{19}$$

The profit function of brown firms reads:

$$\Gamma_t^B = p_t^{Bnet}\left(k_{t-1}^B\right)^{\alpha}\left(z_t h_t^B\right)^{1-\alpha} - w_t h_t^B - r_{kt}^B k_{t-1}^B, \tag{20}$$

where p_t^{Bnet} is the brown price net of taxes and abatement costs:

$$p_t^{Bnet} \equiv \left[p_t^B - \tau_t\,(1-\mu_t)\,\nu_E - \frac{\nu_M}{1+\chi}\mu_t^{1+\chi}\right]. \tag{21}$$

The first order conditions describe the choice of capital, labor, and abatement:

$$w_t h_t^B = (1-\alpha) p_t^{Bnet} y_t^B \tag{22}$$

$$r_{kt}^B k_{t-1}^B = \alpha p_t^{Bnet} y_t^B \tag{23}$$

$$\mu_t = \left(\frac{\nu_E \tau_t}{\nu_M}\right)^{\frac{1}{\chi}}. \tag{24}$$

Equation (24) shows that abatement is an increasing function of the emission tax: if the tax is 0, brown firms do not have any incentive to abate emissions.

The problem of green firms is similar, with the only exception that green firms do not pollute, so they do not pay taxes and abatement costs.

2.5 Capital producers

Capital producers use the output produced by final-good firms and non-depreciated capital from intermediate firms, to produce physical capital. Capital is then sold to green and brown firms. Capital producers solve the following problem:

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

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

where k_t is aggregate capital in the economy and i_t denotes investment. The first order condition reads:

$$q_t \left\{ 1 - \frac{\kappa_I}{2} \left(\frac{i_t}{i_{t-1}} - \theta \right)^2 - \kappa_I \frac{i_t}{i_{t-1}} \left(\frac{i_t}{i_{t-1}} - \theta \right) \right\} + \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} q_{t+1} \left(\frac{i_{t+1}}{i_t} \right)^2 \kappa_I \left(\frac{i_{t+1}}{i_t} - \theta \right) \right] = 1. \tag{25}$$

2.6 Policy

The central bank invests in corporate bonds b_{Ct}^G and b_{Ct}^B and public bonds d_{Ct} issuing nominal reserves RE_t:

$$b_{Ct}^G + b_{Ct}^B + d_{Ct} = \frac{RE_t}{P_t}. \tag{26}$$

Reserves are perfect substitutes with public bonds, so they yield the same nominal interest rate r_t.[9] Define $re_t \equiv \frac{RE_t}{P_t}$ as the real reserve balances. The central bank's real revenues Γ_{Ct} are the following:

$$\Gamma_{Ct} = \left(r_t^G - \frac{r_{t-1}}{\pi_t} \right) b_{Ct-1}^G + \left(r_t^B - \frac{r_{t-1}}{\pi_t} \right) b_{Ct-1}^B.$$

Our model is calibrated to the euro area, where fiscal policy is typically implemented at the country level. Following the DSGE literature that models the euro area (i.e. Christoffel et al., 2008 and Coenen et al., 2018, among others), we are considering the euro area as an individual large country with a shared fiscal policy. This assumption is fairly innocuous: the only relevant fiscal decision in our model is the setting of the carbon tax τ_t, which could be seen as a euro-area coordinated policy to address climate change. The other fiscal variables are assumed to be constant along the balance growth path (public spending g_t) or they are irrelevant as a result of the Ricardian equivalence (total public bonds d_{Gt} and lump-sum taxes t_t). The government budget constraint reads:

$$g_t + \frac{r_{t-1}}{\pi_t} d_{Gt-1} = t_t + d_{Gt} + \tau_t e_t + \Gamma_{Ct}. \tag{27}$$

Given these assumptions, we need to specify a rule for the following policy variables:

$$POL \equiv \left\{ \tau_t, re_t, d_{Ct}, b_{Ct}^B, b_{Ct}^G, r_t \right\}. \tag{28}$$

We assume that public and brown bonds held by the central bank grow at the same rate of the labor-augmenting productivity (thus they are constant along a balanced-growth path). The emission tax τ_t is set such that emissions go linearly to 0 in 2050, in line with EU's commitment to global climate action under the Paris Agreement: the tax increases over time until 2050 and it remains constant afterward. In each policy scenario, we specify a path for for central bank's reserves re_t, with b_{Ct}^G being determined by (26), given d_{Ct} and b_{Ct}^B. The nominal interest rate follows a standard Taylor rule:

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r} \right)^{\rho_r} \left(\frac{\pi_t}{\overline{\pi}} \right)^{\phi_\pi (1-\rho_r)}. \tag{29}$$

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[9] This assumption is not crucial. We could make these assets imperfect substitutes by introducing public bonds in the utility function of households, but we would not gain much for the purpose of the analysis.

2.7 Market clearing

Clearing in the good market implies:

$$y_t = c_t + i_t + g_t + y_t^B \frac{\nu_M}{1+\chi}\mu_t^{1+\chi} + \frac{\kappa_P}{2}\left(\pi_t - \overline{\pi}\right)^2 y_t. \tag{30}$$

Clearing in the corporate bond market:

$$b_t^G = b_{Ht}^G + b_{Ct}^G \tag{31}$$

$$b_t^B = b_{Ht}^B + b_{Ct}^B. \tag{32}$$

Market clearing for public bonds/reserves:

$$d_{Gt} + re_t - d_{Ct} = d_{Ht}. \tag{33}$$

Market clearing in labor and capital markets:

$$h_t = h_t^B + h_t^G \tag{34}$$

$$k_t = k_t^B + k_t^G. \tag{35}$$

2.8 Additional variables

2.8.1 Carbon price

The price of one ton of CO2 (the so called carbon price) is an important statistic in the environmental-macroeconomic literature. In our model, τ_t is the price of one carbon-model unit in terms of output-model units. Let p_t^C be the price of one ton of CO2 in Euro. We compute p_t^C as follows:

$$p_t^C = \frac{s_1 s_2}{s_3}\tau_t, \tag{36}$$

where s_1, s_2, and s_3 are conversion rates defined as follows. The conversion rate s_1 denotes Euro billions per one output-model unit:

$$s_1 = \frac{y^E}{\tilde{y}}, \tag{37}$$

where $y^E = 3022.4$ Euro bil. is the quarterly GDP in the euro area in 2019Q4, while $\tilde{y} = 2.2434$ denotes the initial steady-state detrended output; the conversion rate s_2

denotes Gigatons of Carbon (GtC) per one carbon-model unit:

$$s_2 = \frac{x^{GtC}}{\tilde{x}}, \tag{38}$$

where $x^{GtC} = 870.1476$ GtC is the stock of atmospheric carbon in 2019 and $\tilde{x} = 1947.9$ is the detrended atmospheric carbon in model units in the initial steady state; finally, one ton of carbon is equal to $s_3 = 3.67$ tons of CO2.

2.8.2 Euro-area Pollution

In our model, x_t is the stock of atmospheric carbon generated by world emissions. We also define a measure of euro-area atmospheric carbon, that is pollution generated only by euro-area emissions:

$$x_t^{ea} = (1 - \delta^x)\, x_{t-1}^{ea} + e_t. \tag{39}$$

2.9 Calibration

We calibrate the model to the euro area, at the quarterly frequency. We calibrate most economic parameters following the new version of the New Area-Wide Model (NAWM-II) in Coenen et al. (2018) (Table 1).

Regarding the initial steady-state ratios, we follow the NAWM-II and target $\frac{c}{y}$, $\frac{i}{y}$, and $\frac{g}{y}$ equal to 57.5%, 21.0%, and 21.5%. To match these targets, we calibrate $\alpha = 0.30$ and $\bar{g} = 0.48$.

For the following environmental parameters, we use the calibration in Gibson and Heutel (2020), which update the estimates in Heutel (2012); we set the pollution depreciation δ_x to 0.0035; we calibrate the convexity χ of the abatement function to 1.6; the coefficient in the abatement function ν_M is set to $0.074\,(1 + \chi)$. Moreover, we set the rest-of-the-world emissions to match a steady-state rest-of-the world/EA emission ratio of 15.31, the value observed in 2018: this implies $\tilde{e}^{row} = 13.30$. We set the coefficient in the emission function ν_E to 0.49, in order to target a price of 65 Euro per ton of CO2 under full abatement, a value in line with the literature.

In order to set the weight of the brown output ζ and the elasticity of substitution ξ between the green and the brown outputs we have to define what is green and what is brown. A first option is to interpret y^G and y^B as different energy sources, with a relatively high elasticity of substitution: this is what Carattini et al. (2021) and Giovanardi et al. (2021) do, in models similar to ours. A second option is to to interpret the green as the service sector and the brown as the manufacturing sector, which is more polluting: in this case the elasticity of substitution between the two goods is relatively low. Our results show that Green QE is a limited tool to affect pollution; therefore, in order to be conservative, we choose the first option, given that the second option would magnify our findings: a low elasticity of substitution implies that the two goods are complements, thus a Green QE that boosts the green sector will end up to stimulate also the brown sector. Following Carattini et al. (2021) we set $\xi = 2$; following Giovanardi et al. (2021), who target the renewable energy share in Europe in 2018, we set the weight of the brown good ζ to 0.8. In Section 4, we explore what changes when we interpret the two sectors as services and manufacturing.

The parameters of the bonds' utility functions are specific to our model. Parameters κ_G and κ_B govern the concavity and the convexity of the green bond utility and the brown bond disutility function, respectively; these parameters are relevant for the elasticity of bond demands to the greenium: when κ_G and κ_B are higher, this elasticity is low and households are less willing to change their asset composition, making Green QE more effective. A first option is to set κ_G and κ_B following the studies that use assets in the utility function, where these parameters are calibrated around relatively low values (1 in Alpanda and Kabaca, 2020, 0.15 in Rannenberg, 2021), resulting in large elasticities. A second option is to calibrate directly the elasticity (parameter η in equation 6), in models where different bonds are not perfect substitutes; in an influential work based on a DSGE model, Chen et al. (2012) estimate the short-run elasticity of long-term bond holdings to the spread between long- and short-term rates at a number around 300.[10] Again, in order to give Green QE a chance to be relatively effective, we choose this second option and set $\eta = 300$, trying with the first option in Section 4. This assumption results in relatively large κ_G and κ_B (8.93 and 8.94, respectively).

We also need to calibrate the parameters capturing the relative weight of green and brown bond utility, ν_G and ν_B. We set these parameters such that the annualized brown and green rates are 15 points respectively higher and lower than the real policy rate in the initial steady state. This implies that the annualized greenium is -30 basis points: this value is at the upper ends of estimates in the literature (see for instance Kapraun and Scheins, 2019), but in line with De Santis et al., 2018.[11] Other papers find a much smaller greenium (Liberati and Marinelli, 2021). We choose this relatively high value to be conservative: a lower spread would imply a smaller importance of bond utility functions, making Green QE less effective and strengthening our results, i.e. Green QE is a weak tool to address climate change.[12]

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[10] The estimated median of the distribution parameter ζ' is 0.003274 in Table 2 of Chen et al. (2012); this parameter gives the inverse of the sensitivity of long-term bonds to the spread between long- and short-term rates (equation D23 in Chen et al., 2012's Appendix).

[11] In De Santis et al. (2018), the difference between the CSPP-eligible green industrial spread and the non-green counterpart is around -30 basis points, pre-CSPP announcement.

[12] This calibration implies $\nu_G = 14.9015$ and $\nu_B = 3.10e - 14$. The latter value is extremely low in

Finally, we set the initial central-bank's reserves to GDP ratio to 40%, in order to target the ECB liability/GDP ratio in 2019. We assume that in the initial steady state, the central bank does not hold corporate bonds.

Calibration

Parameter	**Description**	**Value**	**Notes**
β	Discount factor	0.9988	Real rate of 2% annually (NAWM-II)
φ	Inverse of Frisch elasticity	2	NAWM-II
ε	Elas. of subst. differentiated goods	3.8571	NAWM-II
α	Share of capital in production	0.2975	$\frac{i}{y} = 0.21$ (NAWM-II)
κ_P	Price adjustment costs	71.5603	NAWM-II
δ	Depreciation rate	2.5%	NAWM-II
θ	Growth rate of trend variables	1.0038	NAWM-II
κ_I	Investment adjustment cost	10.78	NAWM-II
π	SS inflation	1.005	ECB target
$\tilde{g}$	Public spending	0.4823	$g/y = 0.215$ (NAWM-II)
ϕ_π	Taylor rule coefficient	2.74	NAWM-II
ρ_r	Inertia of Taylor rule	0.93	NAWM-II
ζ	Weight of brown good	0.8	Giovanardi et al. (2021)
ξ	Elas. of subst. brown-green good	2	Carattini et al. (2021)
δ_x	Pollution depreciation	0.0035	Gibson and Heutel (2020)
$\tilde{e}^{row}$	Emissions in the rest of the world	13.2974	$\frac{e^{row}}{e} = 15.31$
χ	Convexity of abatement function	1.6	Gibson and Heutel (2020)
ν_M	Coefficient in the abatement function	0.1924	Gibson and Heutel (2020)
ν_E	Coefficient in the emission function	0.4854	$p^C = 65$ under $\mu = 1$
ν_G	Bond utility parameter	14.9015	$400\left(r^G - rr\right) = -0.0015$
ν_B	Bond utility parameter	3.0996×10^{-14}	$400\left(r^B - rr\right) = 0.0015$
κ_G, κ_B	Bond elasticity	8.9300, 8.9367	$\eta = 300$
$\tilde{re}$	CB reserves	3.5895	$\frac{re}{4y} = 0.4$
$\tilde{b}_C^G, \tilde{b}_C^B$	CB corporate bonds	0, 0	NAWM-II

Table 1: Calibrated parameters.

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order to offset an otherwise huge marginal disutilty of brown bonds $\nu_B b_{HB}^{\kappa_B}$, given $\kappa_B = 8.92$.

3 Analysis

In this section, we solve the model in perfect foresight: we start from a steady sate where agents do not expect any shift in the environmental policies, then the whole set of policies is announced, and households can perfectly foresee the path of fiscal and monetary policies until the new steady state is reached. First, we simulate the transition from the initial steady state to an economy with zero emissions. Second, we study the effects of an increase in green bonds held by the central bank, throughout the transition.

3.1 The transition to a green economy

We assume that period 0 corresponds to 2019Q4, when the government introduces an emission tax that increases linearly for 120 quarters, such that from 2050 on all emissions are abated; in order to fully abate emissions, the carbon price is around 65 Euro per ton of CO2. In Figure 1 we plot the transition to the new steady state with zero emissions: the variables are in percentage deviations with respect to the value they would have had with no increase in the emission tax.[13]

Pollution follows a slow law of motion and after one century has still not reached the new steady state; we are assuming that emissions in the rest of the world are not abated, so in the new steady state the reduction in global pollution is far from 100%.[14] The consumption fall depends on the higher abatement costs, which are around 5% of steady state GDP in case of full abatement. We highlight that the final reduction in consumption would be the same even under different speeds of the transition. However, in our model we are not factoring in the TFP costs of pollution, so we are somewhat over-estimating the consumption decrease.

The shift of resources toward abatement costs and the higher production costs drive a fall in investment too, which in turn reduces the stock of capital. The output fall is smaller than the consumption and investment decrease, given that we are including abatement costs in the definition of output: to accomplish that, in the new steady state households work more. The tax shifts resources from the brown to the green sector, which experiences a large expansion. We find that the transition to a green economy is deflationary, despite the increases in the marginal costs of brown firms associated with the tax: inflation falls on impact, and then gradually comes back to the initial steady state. This result relies on the permanent nature of the tax. For the economy, the emission

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[13] Given that TFP grows over time at a constant rate, consumption is much higher in 2050 with respect to 2020: the 10% fall in the new steady state is relative to the scenario with no environmental policy.

[14] If we assume that the rest of the world reduces emissions too, pollution would slowly go to zero. The other variables would not be affected.

tax works like a permanent negative TFP shock, which makes more costly to produce a given amount of output forever. In this class of models, permanent negative TFP shocks reduce both output and inflation.[15] For households future consumption is lower than the current one, resulting in a downward shift in the aggregate demand and in a reduction in the CPI level. The fall in inflation induces the central bank to reduce the policy rate along the transition.

3.2 Green QE along the transition

We assume that Green QE consists of a 50% increase in the stock of central bank's reserves, which finance purchase of green bonds only.

We simulate three different types of green purchases (Figure 2). In the blue solid line we consider a gradual permanent increase in the stock of green bonds until to year 2050 (GQE1). In the red dotted line, we consider a one-shot permanent increase in the stock of green bonds by the central bank (GQE2). In the black dashed line, we simulate a transitory increase in the stock of green bonds, which gradually dies out over time until 2050, when the amount of green bonds comes back to the initial level (GQE3). During the transition, the central bank keeps using the Taylor rule for the nominal interest rate.

In all scenarios, the purchase of green bonds by the central bank is only partially matched by households' sale, and leads to the issuance of new green bonds. Given that households enjoy utility by holding corporate bonds, they sell green bonds to the extent that the rate on green bonds decreases with respect to the brown rate and to the real policy rate. Green firms face a lower interest rate and expand capital and output. The higher supply of green output reduces its price: intermediate-good firms replace brown output with green output. The fall in brown production reduces emissions and pollution.

The timing of the purchases turns out to be crucial for the effectiveness of Green QE. Given that in the long run emissions go to zero anyway as a result of the emission tax, it is more useful to reduce emissions in the short/medium run, in order to get a larger effect on the pollution stock. The tax induces firms to spend in abatement, which in turn implies a lower reduction in emissions for any decrease in brown output (equation 17). This explains the greater effectiveness of earlier permanent and transitory purchases (GQE2 and GQE3), with respect to permanent gradual purchases (GQE1). Remarkably, the transitory purchase has an effect comparable to the permanent-one shot purchase, and it does not break the market-neutrality principle in the long-run.

Green QE affects also aggregate variables. In the short run, the expansion in the green sector is larger than the contraction in the brown sector, and output rises. Consumption

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[15] See for instance the impulse response function to a positive and permanent TFP shock in Christoffel et al. (2008).

initially falls, to finance higher investment in green capital, and then it increases. The rise in aggregate capital drives a positive response in labor, which is more productive. Under GQE2 and GQE3 the rise in aggregate demand boosts the inflation rate, which triggers a contractionary response of the central bank.[16] The dynamics are much slower for GQE1, which is more gradual relatively to the other two scenarios. In the long run, GQE3 is transitory and its effects die out; under GQE1 and GQE2, the economy reaches a new steady state with a higher level of economic activity, which is driven by a permanently lower interest rate in the green sector. From a quantitative point of view, the effects of Green QE on global and EA pollution are never larger than 0.012% and 0.2% respectively compared to the initial level. These small effects are in line with the results of Ferrari and Nispi Landi (2021) and hold even in a model where Green QE has a long-run impact.

The size of the policy is arbitrary, but this is an instrument that has not been used yet and we do not have a benchmark size of the purchase. Thus, we also study larger and smaller reserve increases, to find out whether the effects of Green QE are linear in the size of purchases: we consider GQE3 and simulate different sizes of the initial increase in reserves (Figure 3). We show that the effects of Green QE on pollution and macroeconomic variables are convex in the size of Green QE: for instance, the reduction in pollution when the stock of reserves increases by 75% (Figure 3, black dashed line) is more than double compared to the reduction after a 50% increase (Figure 3, blue solid line). This non-linearity hinges on the concavity of green-bond utility and on the convexity of brown-bond disutility. This implies that the disutility of holding less green and more brown bonds is particularly large when the size of Green QE is big: in that case, households accept to sell green and buy brown bonds only if the latter yield a much higher return.

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[16] These impulse responses are in deviations compared to the scenario in Figure 1: hence, under Green QE the nominal interest rate falls by less.

The transition to a green economy

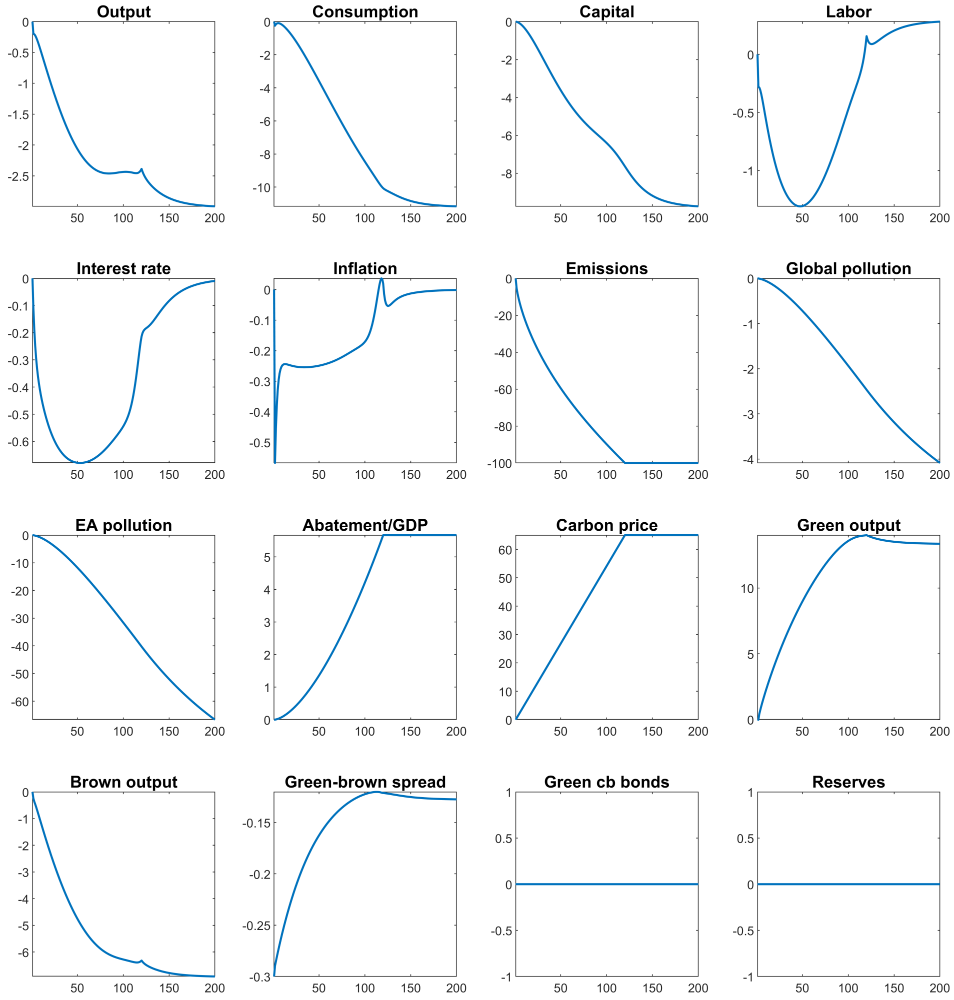

Figure 1: Transition to a zero-emission economy, driven by an emission tax. Variables are in percentage deviations from the path they would have followed with no environmental policy except for inflation, interest rate, and spread, whose responses are in quarterly deviations reported at annual rates, and for carbon price, whose response is expressed in level deviations. The path for the emission tax is announced in period 0.

The impact of Green QE

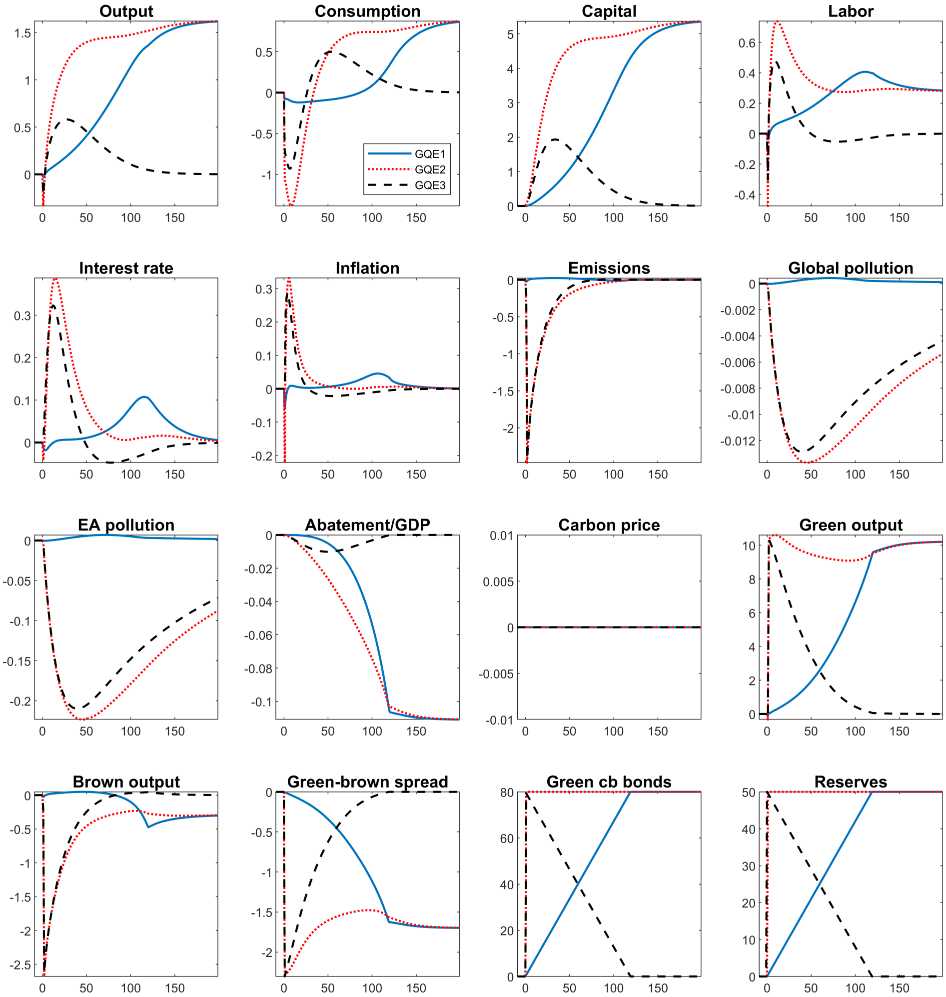

Figure 2: Variables are plotted as the percentage deviation from the initial steady state in the scenario with Green QE minus the percentage deviation from the initial steady state in the scenario with no Green QE, shown in Figure 1, except for interest rate, inflation, and spread, whose responses are in annualized level deviations, and for green bonds, whose response is in deviation from steady-state GDP. Blue solid line: Green QE is gradual and permanent. Red dotted line: Green QE immediately jumps to the new steady state in period 1. Black dashed line: Green QE is transitory. In all scenarios, Green QE is announced in period 0.

Different Green QE Sizes

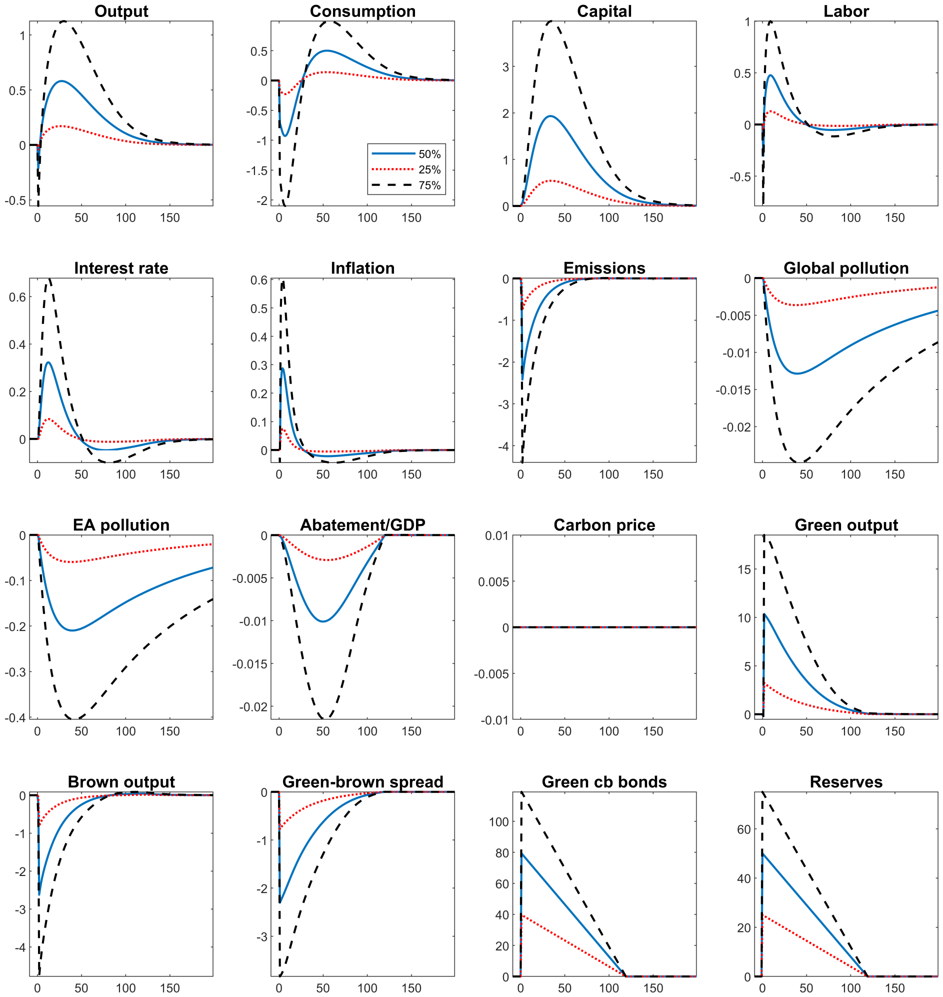

Figure 3: Variables are plotted as the percentage deviation from the initial steady state in the scenario with Green QE, except for interest rate, inflation, and spread, whose responses are in annualized level deviations, and for green bonds, whose response is in deviation from steady-state GDP. Blue solid line: reserves increase by 50%. Red dotted line: reserves increase by 25%. Black dashed line: reserves increase by 75%. In all scenarios, Green QE is announced in period 0.

4 Additional exercises

In this section we carry out three additional exercises. First, we simulate a Green QE without the presence of the carbon tax. Second, we modify the weight of the brown good and the elasticity of substitution between the green and the brown output in the final-good bundle. Third, we change the parameter of the bond utility functions. The figures of this section are in the Appendix.

4.1 Can Green QE lead the transition?

The marginal effects of Green QE on top of a carbon tax are small on the stock of pollution. The carbon tax is effective in driving the euro area to a zero-emission economy and Green QE can provide only a small additional contribution. Can Green QE alone lead the transition, without the introduction of carbon tax? We simulate the effects of a one shot permanent increase in Green QE (GQE2), keeping the carbon tax to 0 (Figure A.1, red dotted line line). We compare this exercise with the blue solid line in Figure 2 (also reported in Figure A.1), which shows the marginal contribution of Green QE on top of the carbon tax. The effectiveness of Green QE in reducing emissions is decreasing in the level of the carbon tax: as already observed in the previous section, the tax induces firms to spend in abatement, which in turn partially reduces the link between emissions and brown output (equation 17). Green QE can reduce emissions only by its impact on brown interest rates, and thus on brown production: if the link between brown production and emissions is stronger (for instance when $\tau = \mu = 0$), Green QE gets more effective. A larger reduction in emissions also drives a larger, but still small, decrease in the stock of pollution.

4.2 Brown sector's size and elasticity of substitution

In the baseline scenario, we interpret the green and the brown good as different sources of energy, in line with Carattini et al. (2021) and Giovanardi et al. (2021). In this section, we interpret the green as the service sector and the brown as the manufacturing sector. As shown by Papoutsi et al. (2021), in the euro area emissions are generated mostly by the secondary sector, whose capital income accounts for 35% of total capital income in the euro area: we calibrate $\zeta = 0.35$. The elasticity of substitution between services and manufacturing goods is relatively low: we follow Gomes et al. (2012), a DSGE model of the euro area, and calibrate this elasticity of substitution to 0.5.[17] Under the new calibration (Figure A.2, red dotted line) Green QE *increases* emissions. This policy

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[17] In changing ζ and ξ, we also modify the parameters that are set to match some steady-state targets.

drives a reduction in the green rate that boosts the green sector. Although the brown rate decreases, as the green and the brown goods are complements, the demand for the brown good rises, brown firms increase production and emissions rise.

4.3 Greenium and bond elasticities

In the baseline calibration, we have set a steady-state greenium in the upper end of estimates found in the literature; moreover, we have calibrated the curvature of the bond utility functions to relatively high values, in order to give a change to Green QE to be powerful. In this section, we calibrate these parameters to lower values. Specifically, we set the annualized greenium to 5 basis points (as found in Liberati and Marinelli, 2021),[18] and we calibrate $\kappa_G = \kappa_B = 1$, which means a log green bond utility and a quadratic brown bond disutility, which are values more in line with the literature.[19] We simulate the three types of Green QE (Figure A.3): not surprisingly, we find that Green QE has much smaller effects, given its limited ability to affect the green and brown interest rates. In particular the effect on emission is two orders of magnitude smaller, compared to the baseline scenario.

5 Concluding Remarks

We set up a model to study the effects of the transition toward a carbon neutral economy on macroeconomic variables and to explore the role of asset purchases by the central bank along the transition.

First, we simulate the impact of a carbon tax that leads to carbon neutrality by 2050 as established in the plan by the European commission to reach the Paris agreement goals. Second, we explored the possible role of central bank's active monetary policies to foster the transition. We found that in our setup the role for unconventional monetary policy is positive but small. Within these limits, the analysis suggests that the benefits from the central bank intervention are more significant if they take place in the early stage of the transition, while their effectiveness decreases as the environmental fiscal policy is enacted: a temporary QE implemented in the early stage of the transition is more effective than a permanent but gradual purchase program. We also find that the elasticity of substitution between green and brown goods is a crucial parameter for the effectiveness of Green QE: in our baseline calibration, we set this elasticity higher than one; but under an elasticity lower than one, i.e. the goods are complements, Green QE could even raise emissions.

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[18] Specifically, we set $400\left(rr - r^B\right) = 0.00025 = -400\left(r^G - rr\right)$.

[19] This calibration implies $\nu_G = 1.5901e-04$ and $\nu_B = 3.7210e-06$.

Our model is a stylized version of the euro area economy and we have ignored some potentially relevant channels. First, in our model pollution does not affect TFP, hence we are ignoring potentially relevant feedback effects from the environment to the economic activity: in our model, the negative effects of climate change are underestimated. Second, the model could be enriched with an R&D sector, which can produce innovative green technologies that do not pollute or that reduce abatement spending, other things equal. Third, it would be interesting to model abatement spending as an investment una-tantum cost, as opposed to a cost that firms pay period by period. We leave these extensions for future research.

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Appendix

A Model Equations

In this section, we list the full set of the model equations. We have detrended the non-stationary variables, by dividing them by the labor-augmenting productivity z_t, which grows at gross rate θ: these variables are denoted with a tilde. There are 28 equations for the following 28 endogenous variables:

$$X_t^{end} \equiv \quad \Big[\tilde{c}_t, \tilde{i}_t, \tilde{y}_t, \tilde{k}_t, h_t, \tilde{w}_t, q_t, p_t^I, \pi_t, r_t, r_t^B, r_t^G, \tilde{b}_{Ht}^G, \tilde{b}_{Ht}^B,$$
$$\tilde{b}_{Ct}^G, \mu_t, p_t^G, p_t^B, \tilde{k}_t^G, \tilde{k}_t^B, h_t^G, h_t^B, r_{kt}^G, r_{kt}^B, \tilde{e}_t, \tilde{x}_t, \tilde{y}_t^G, \tilde{y}_t^B\Big].$$

There are 2 exogenous variables:

$$X_t^{exo} \equiv \quad [\tau_t, \widetilde{re}_t].$$

The 29 equations are the following. Labor supply condition:

$$\tilde{c}_t h_t^{\varphi} = \tilde{w}_t. \tag{A.1}$$

Euler equation for public bonds:

$$1 = \beta \mathbb{E}_t \left(\frac{\tilde{c}_t}{\tilde{c}_{t+1}\theta} \frac{r_t}{\pi_{t+1}} \right). \tag{A.2}$$

Euler equation for green and brown bonds:

$$1 = \beta \mathbb{E}_t \left[\frac{\tilde{c}_t}{\tilde{c}_{t+1}\theta} r_{t+1}^G \right] + \nu_G \tilde{c}_t \left(\tilde{b}_{Ht}^G \right)^{-\kappa_G} \tag{A.3}$$

$$1 = \beta \mathbb{E}_t \left[\frac{\tilde{c}_t}{\tilde{c}_{t+1}\theta} r_{t+1}^B \right] - \nu_B \tilde{c}_t \left(\tilde{b}_{Ht}^B \right)^{\kappa_B}. \tag{A.4}$$

Production function of intermediate firms:

$$\tilde{y}_t = \left[(1-\zeta)^{\frac{1}{\xi}} \left(\tilde{y}_t^G \right)^{\frac{\xi-1}{\xi}} + \zeta^{\frac{1}{\xi}} \left(\tilde{y}_t^B \right)^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}. \tag{A.5}$$

If $\xi = 1$, the production function takes the following form:

$$\tilde{y}_t = \left(\tilde{y}_t^G \right)^{1-\zeta} \left(\tilde{y}_t^B \right)^{\zeta}.$$

Demand of green and brown output:

$$\tilde{y}_t^G = (1-\zeta)\left(\frac{p_t^G}{p_t^I}\right)^{-\xi}\tilde{y}_t \tag{A.6}$$

$$\tilde{y}_t^B = \zeta\left(\frac{p_t^B}{p_t^I}\right)^{-\xi}\tilde{y}_t. \tag{A.7}$$

Phillips curve:

$$\pi_t\left(\pi_t-\overline{\pi}\right) = \beta\mathbb{E}_t\left[\frac{\tilde{c}_t}{\tilde{c}_{t+1}}\frac{\tilde{y}_{t+1}}{\tilde{y}_t}\pi_{t+1}\left(\pi_{t+1}-\overline{\pi}\right)\right] + \frac{\varepsilon}{\kappa_P}\left(p_t^I - \frac{\varepsilon-1}{\varepsilon}\right). \tag{A.8}$$

Green and brown production functions:

$$\tilde{y}_t^G = \left(\frac{\tilde{k}_{t-1}^G}{\theta}\right)^{\alpha}\left(h_t^G\right)^{1-\alpha} \tag{A.9}$$

$$\tilde{y}_t^B = \left(\frac{\tilde{k}_{t-1}^B}{\theta}\right)^{\alpha}\left(h_t^B\right)^{1-\alpha}. \tag{A.10}$$

Green and brown labor demands:

$$\tilde{w}_t h_t^G = (1-\alpha)\, p_t^G \tilde{y}_t^G \tag{A.11}$$

$$\tilde{w}_t h_t^B = (1-\alpha)\left[p_t^B - \tau_t\left(1-\mu_t\right)\nu_E - \frac{\nu_M}{1+\chi}\mu_t^{1+\chi}\right]\tilde{y}_t^B. \tag{A.12}$$

Green and brown capital demand:

$$r_{kt}^G\frac{\tilde{k}_{t-1}^G}{\theta} = \alpha p_t^G\tilde{y}_t^G \tag{A.13}$$

$$r_{kt}^B\frac{\tilde{k}_{t-1}^B}{\theta} = \alpha\left[p_t^B - \tau_t\left(1-\mu_t\right)\nu_E - \frac{\nu_M}{1+\chi}\mu_t^{1+\chi}\right]\tilde{y}_t^B. \tag{A.14}$$

Definition of rental rates of capital:

$$r_{kt}^G = r_t^G q_{t-1} - (1-\delta)\, q_t \tag{A.15}$$

$$r_{kt}^B = r_t^B q_{t-1} - (1-\delta)\, q_t. \tag{A.16}$$

Optimal abatement effort:

$$\mu_t = \left(\frac{\nu_E\tau_t}{\nu_M}\right)^{\frac{1}{\chi}}. \tag{A.17}$$

Emission function:

$$\tilde{e}_t = (1 - \mu_t)\, \nu_E \tilde{y}_t^B. \tag{A.18}$$

Law of motion of pollution:

$$\tilde{x}_t = (1 - \delta^x)\, \frac{\tilde{x}_{t-1}}{\theta} + \tilde{e}_t + \tilde{e}^{row}. \tag{A.19}$$

Tobin Q evolution:

$$\begin{aligned} 1 =& q_t \left[1 - \frac{\kappa_I}{2}\left(\frac{\tilde{i}_t}{\tilde{i}_{t-1}}\theta - \theta\right)^2 - \kappa_I \frac{\tilde{i}_t}{\tilde{i}_{t-1}}\theta \left(\frac{\tilde{i}_t}{\tilde{i}_{t-1}}\theta - \theta\right)\right] + \\ &+ \beta \mathbb{E}_t \left[\frac{\tilde{c}_t}{\tilde{c}_{t+1}\theta} q_{t+1} \left(\frac{\tilde{i}_{t+1}}{\tilde{i}_t}\theta\right)^2 \kappa_I \left(\frac{\tilde{i}_{t+1}}{\tilde{i}_t}\theta - \theta\right)\right]. \end{aligned} \tag{A.20}$$

Law of motion of capital:

$$\tilde{k}_t = (1 - \delta)\, \frac{\tilde{k}_{t-1}}{\theta} + \left[1 - \frac{\kappa_I}{2}\left(\frac{\tilde{i}_t}{\tilde{i}_{t-1}}\theta - \theta\right)^2\right] \tilde{i}_t. \tag{A.21}$$

Resource constraint:

$$\tilde{y}_t = \tilde{c}_t + \tilde{i}_t + \tilde{g} + \tilde{y}_t^B \frac{\nu_M}{1+\chi}\mu_t^{1+\chi} + \frac{\kappa_P}{2}\left(\pi_t - \overline{\pi}\right)^2 \tilde{y}_t. \tag{A.22}$$

Market clearing for labor and capital:

$$h_t = h_t^B + h_t^G \tag{A.23}$$

$$\tilde{k}_t = \tilde{k}_t^B + \tilde{k}_t^G. \tag{A.24}$$

Market clearing for green and brown bonds:

$$q_t \tilde{k}_t^G = \tilde{b}_{Ht}^G + \tilde{b}_{Ct}^G \tag{A.25}$$

$$q_t \tilde{k}_t^B = \tilde{b}_{Ht}^B + \tilde{b}_C^B. \tag{A.26}$$

Taylor rule:

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r}\right)^{\rho_r} \left(\frac{\pi_t}{\overline{\pi}}\right)^{\phi_\pi (1-\rho_r)}. \tag{A.27}$$

Balance sheets of the central bank:

$$\tilde{b}_{Ct}^G + \tilde{b}_C^B + \tilde{d}_C = r\tilde{e}_t. \tag{A.28}$$

We also define the price of carbon and the EA pollution as follows:

$$p_t^C = \frac{s_1 s_2}{s_3}\tau_t \tag{A.29}$$

$$\tilde{x}_t^{ea} = (1-\delta^x)\,\frac{\tilde{x}_{t-1}^{ea}}{\theta} + \tilde{e}_t. \tag{A.30}$$

B Initial Steady State

We compute the initial steady state using the following strategy. We simplify the model in a system of three equations and three variables (y, p^B,e). We set $\gamma^G \equiv r^G - rr$ and $\gamma^B \equiv r^B - rr$ ex ante and compute ν_G and ν_B ex post. We calibrate ex ante the real interest rate $rr = \frac{r}{\pi}$ and compute β ex post. We set $I \equiv \frac{i}{y}$ and $G \equiv \frac{g}{y}$ ex ante and compute α and $\tilde{g}$ ex post. We set $p^C = 65$ when $\tau = 1$, computing ν_E ex post. We set $RoW \equiv \frac{\tilde{e}^{row}}{\tilde{e}}$ and compute $\tilde{e}^{row}$ ex post. In the initial steady state, $\tau = 0$, which implies $\mu = 0$.

Using the Euler equation for bonds,

$$\beta = \frac{\theta}{rr}.$$

Using the Phillips Curve and the Euler equations, we get:

$$\pi = \bar{\pi}$$

$$r = \frac{\bar{\pi}\theta}{\beta}$$

$$r^G = rr + \gamma^G$$

$$r^B = rr + \gamma^B$$

$$r_k^B = r^B - (1-\delta)$$

$$r_k^G = r^G - (1-\delta)$$

$$q = 1$$

$$p_I = \frac{\varepsilon - 1}{\varepsilon}.$$

Use the definition of p_I to find p^G:

$$\begin{aligned}\left(p^I\right)^{1-\xi} &= \left[(1-\zeta)\left(p^G\right)^{1-\xi} + \zeta\left(p^B\right)^{1-\xi}\right] \\ \left(p^G\right)^{1-\xi} &= \frac{1}{1-\zeta}\left[\left(p^I\right)^{1-\xi} - \zeta\left(p^B\right)^{1-\xi}\right] \\ p^G &= \left\{\frac{1}{1-\zeta}\left[\left(p^I\right)^{1-\xi} - \zeta\left(p^B\right)^{1-\xi}\right]\right\}^{\frac{1}{1-\xi}}.\end{aligned}$$

Use the input demands to find $\tilde{y}^B$ and $\tilde{y}^G$:

$$\begin{aligned}\tilde{y}^B &= \zeta\left(\frac{p^B}{p^I}\right)^{-\xi}\tilde{y} \\ \tilde{y}^G &= (1-\zeta)\left(\frac{p^G}{p^I}\right)^{-\xi}\tilde{y}.\end{aligned}$$

Given $\tilde{y}$, we find s_1:

$$s_1 = \frac{y^E}{\tilde{y}}.$$

Find $\tilde{e}^{row}$ using RoW:

$$\tilde{e}^{row} = RoW \cdot \tilde{e}.$$

Given $\tilde{e}$, we find $\tilde{x}$ using the law of motion of atmospheric carbon:

$$\tilde{x} = \frac{\tilde{e} + e^{row}}{1 - \frac{1-\delta^x}{\theta}}.$$

Given $\tilde{x}$, we can find s_2:

$$s_2 = \frac{x^{GtC}}{\tilde{x}}.$$

When $\mu = 1$, $\tau^{full} = \frac{\nu_M}{\nu_E}$; hence, under full abatement it holds:

$$\begin{aligned}p^{Cfull} &= \frac{s_1 s_2}{s_3}\tau^{full} \\ p^{Cfull} &= \frac{s_1 s_2}{s_3}\frac{\nu_M}{\nu_E} \\ \nu_E &= \frac{s_1 s_2}{s_3}\frac{\nu_M}{p^{Cfull}}\end{aligned}$$

and we get ν_E. Given the investment ratio, we find $\tilde{i}$ and $\tilde{k}$:

$$\begin{aligned}\tilde{i} &= I\tilde{y}\\ \tilde{k} &= \frac{\tilde{i}}{\left(1-\frac{1-\delta}{\theta}\right)}.\end{aligned}$$

By the capital demands we know that:

$$\begin{aligned}\tilde{k}^G &= \alpha\theta\frac{p^G\tilde{y}^G}{r_k^G}\\ \tilde{k}^B &= \alpha\theta\frac{\tilde{y}^B}{r_k^B}\left[p^B-\tau\left(1-\mu_t\right)\nu_E-\frac{\nu_M}{1+\chi}\mu^{1+\chi}\right].\end{aligned}$$

Sum the capital demands:

$$\tilde{k} = \alpha\theta\left\{\frac{p^G\tilde{y}^G}{r_k^G}+\frac{\tilde{y}^B}{r_k^B}\left[p^B-\tau\left(1-\mu\right)\nu_E-\frac{\nu_M}{1+\chi}\mu^{1+\chi}\right]\right\},$$

and find α:

$$\alpha = \frac{\tilde{k}}{\theta\left\{\frac{p^G\tilde{y}^G}{r_k^G}+\frac{\tilde{y}^B}{r_k^B}\left[p^B-\tau\left(1-\mu_t\right)\nu_E-\frac{\nu_M}{1+\chi}\mu^{1+\chi}\right]\right\}},$$

and then use the capital demands to find $\tilde{k}^G$ and $\tilde{k}^B$. Use the production function to find h^B and h^B:

$$\begin{aligned}h^B &= \left[\frac{\tilde{y}^B}{a\left(\frac{\tilde{k}^B}{\theta}\right)^{\alpha}}\right]^{\frac{1}{1-\alpha}}\\ h^G &= \left[\frac{\tilde{y}^G}{a\left(\frac{\tilde{k}^G}{\theta}\right)^{\alpha}}\right]^{\frac{1}{1-\alpha}}.\end{aligned}$$

Bonds held by households:

$$\begin{aligned}\tilde{b}_H^G &= \tilde{k}^G-\tilde{b}_C^G\\ \tilde{b}_H^B &= \tilde{k}^B-\tilde{b}_C^B,\end{aligned}$$

given that in the initial steady state we know $\tilde{b}_C^G = \tilde{b}_C^B$ (they are both 0). Using the labor demand in the green sector we can find w:

$$w = \frac{(1-\alpha)\,\tilde{p}^G \tilde{y}^G}{h^G}.$$

Given the public spending ratio, we find $\tilde{g}$:

$$\tilde{g} = G\tilde{y}.$$

We find consumption by the resource constraint:

$$\tilde{c} = \tilde{y} - \tilde{i} - \tilde{g} - \tilde{y}^B \frac{\nu_M}{1+\chi}\mu^{1+\chi}.$$

Aggregate labor is given by:

$$h = h^B + h^G.$$

Using the bond Euler equation, we find the utility parameters:

$$\begin{aligned}
1 &= \frac{\beta}{\theta} r^G + \nu_G \tilde{c} \left(\tilde{b}_H^G\right)^{-\kappa_G} \\
\nu_G &= \frac{\left(1 - \frac{\beta}{\theta} r^G\right)}{\tilde{c}\left(\tilde{b}_H^G\right)^{-\kappa_G}}
\end{aligned}$$

$$\begin{aligned}
1 &= \frac{\beta}{\theta} r^B - \nu_B \tilde{c} \left(\tilde{b}_H^B\right)^{\kappa_B} \\
\nu_B &= \frac{\frac{\beta}{\theta} r^B - 1}{\tilde{c}\left(\tilde{b}_H^B\right)^{\kappa_B}}
\end{aligned}$$

We are left with three equations in three unknowns:

$$\begin{aligned}
\tilde{w} h^B &= (1-\alpha)\left[p^B - \tau(1-\mu)\nu_E - \frac{\nu_M}{1+\chi}\mu^{1+\chi}\right]\tilde{y}^B \\
\tilde{w} &= \tilde{c} h^{\varphi} \\
\tilde{e} &= (1-\mu)\nu_E \tilde{y}_B.
\end{aligned}$$

C Final Steady State

In the final steady state, we set $\mu = 1$, which implies $\tilde{e} = 0$. Compared to the procedure for the initial steady state, we let $\widetilde{r^G}$, and $\widetilde{r^B}$ to be determined ex post. We simplify the model to a system of four equations and four variables: $\left\{y, p^B, r^G, r^B\right\}$. Following the same steps to compute the initial steady state, we end up with the following system of equations:

$$\begin{aligned}
\tilde{w}h^B &= (1-\alpha)\left[p^B - \tau\left(1-\mu\right)\nu_E - \frac{\nu_M}{1+\chi}\mu^{1+\chi}\right]\tilde{y}^B \\
\tilde{w} &= \tilde{c}h^{\varphi} \\
1 &= \frac{\beta}{\theta}r^G + \nu_G\tilde{c}\left(\tilde{b}_H^G\right)^{-\kappa_G} \\
1 &= \frac{\beta}{\theta}r^B - \nu_B\tilde{c}\left(\tilde{b}_H^B\right)^{\kappa_B}.
\end{aligned}$$

D Additional figures and table

Green QE without fiscal policy

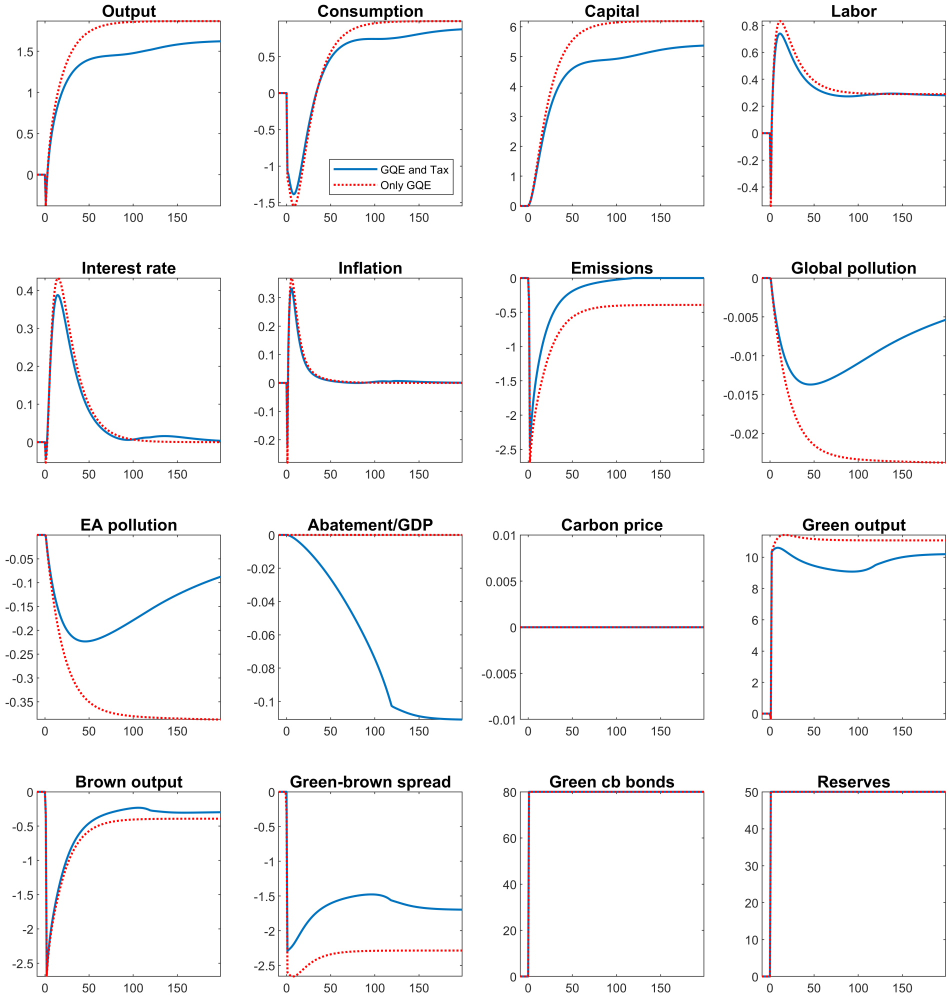

Figure A.1: Variables are plotted as the percentage deviation from the initial steady state in the scenario with Green QE minus the percentage deviation from the initial steady state in the scenario with no Green QE, except for interest rate, inflation, and spread, whose responses are in annualized level deviations, and for green bonds, whose response is in deviation from steady-state GDP. Blue solid line: both carbon tax and Green QE. Red dotted line: only Green QE, no carbon tax.

Green QE: Changing ζ and ξ

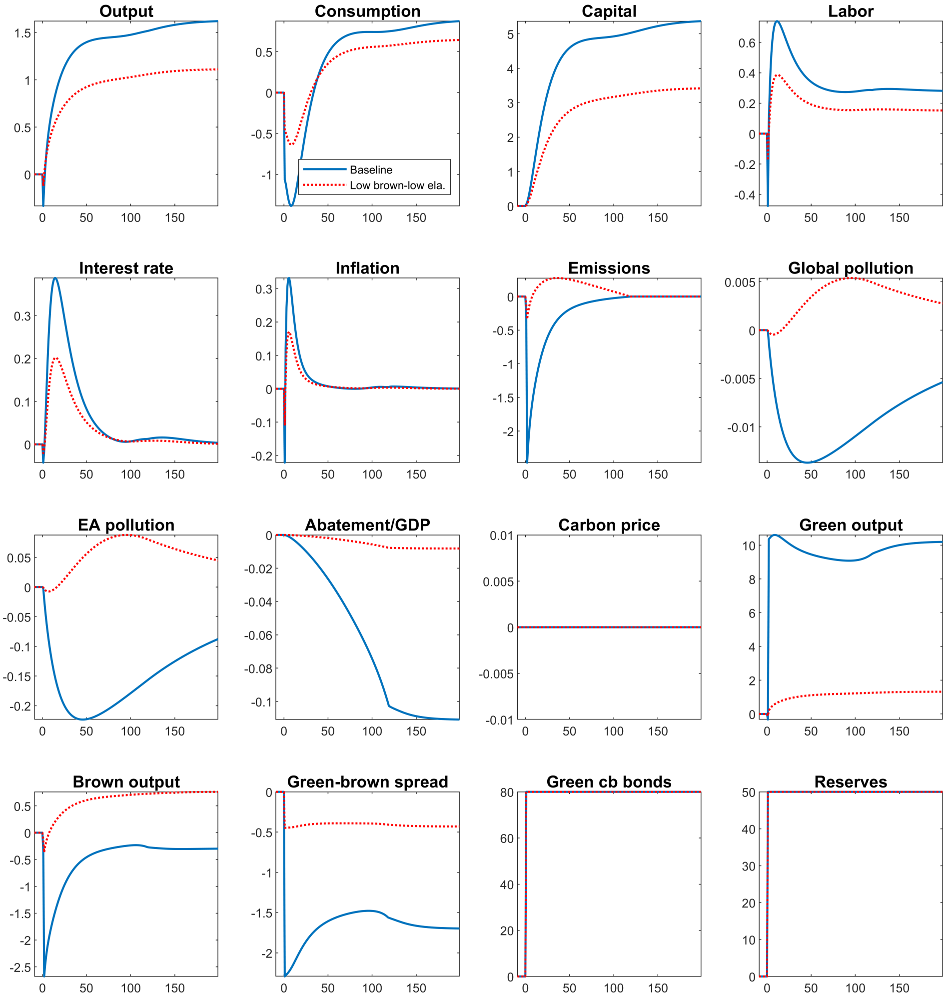

Figure A.2: Variables are plotted as the percentage deviation from the initial steady state in the scenario with Green QE minus the percentage deviation from the initial steady state in the scenario with no Green QE, except for interest rate, inflation, and spread, whose responses are in annualized level deviations, and for green bonds, whose response is in deviation from steady-state GDP. Blue solid line: $\zeta = 0.8$, $\xi = 2$. Red dotted line: $\zeta = 0.35$, $\xi = 0.5$.

Green QE: changing the bond utility function

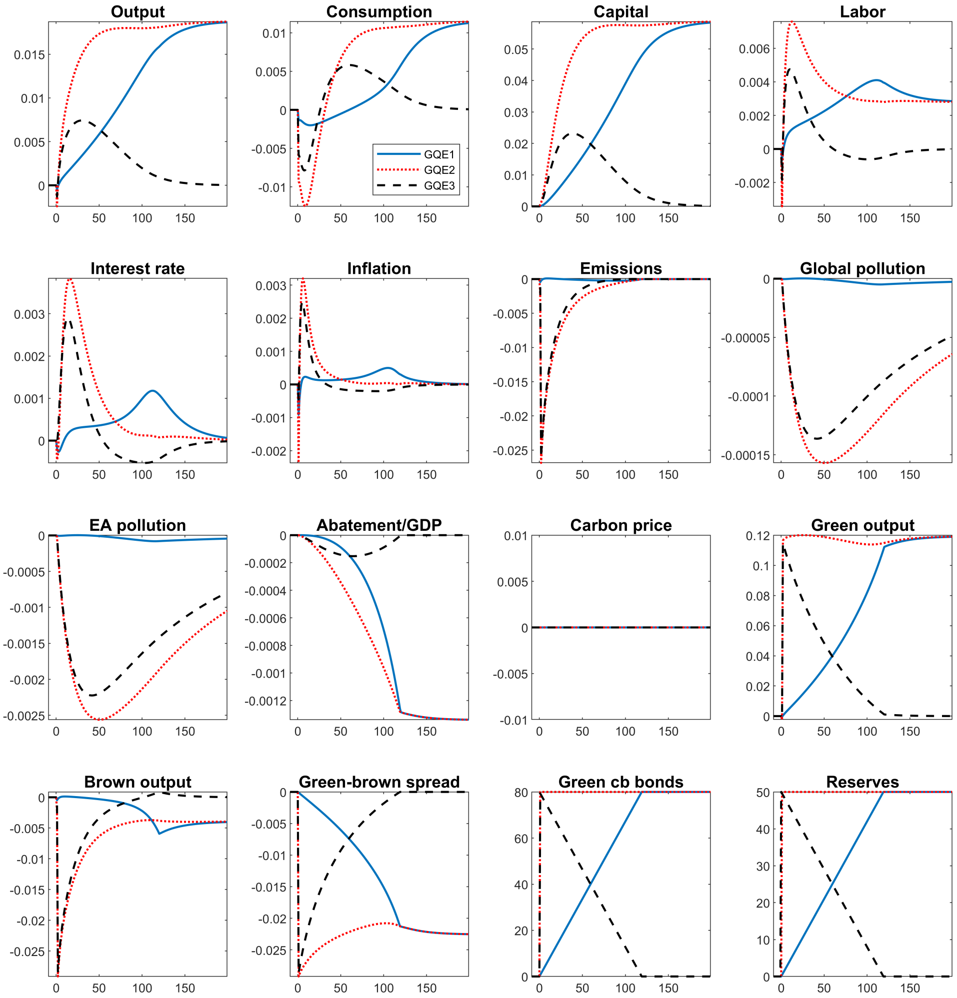

Figure A.3: We set $400\left(rr - r^B\right) = 0.00025 = -400\left(r^G - rr\right)$ and $\kappa_B = \kappa_G = 1$. Variables are plotted as the percentage deviation from the initial steady state in the scenario with Green QE minus the percentage deviation from the initial steady state in the scenario with no Green QE, shown in Figure 1, except for interest rate, inflation, and spread, whose responses are in annualized level deviations, and for green bonds, whose response is in deviation from steady-state GDP. Blue solid line: Green QE is gradual and permanent. Red dotted line: Green QE immediately jumps to the new steady state in period 1. Black dashed line: Green QE is transitory. In all scenarios, Green QE is announced in period 0.

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