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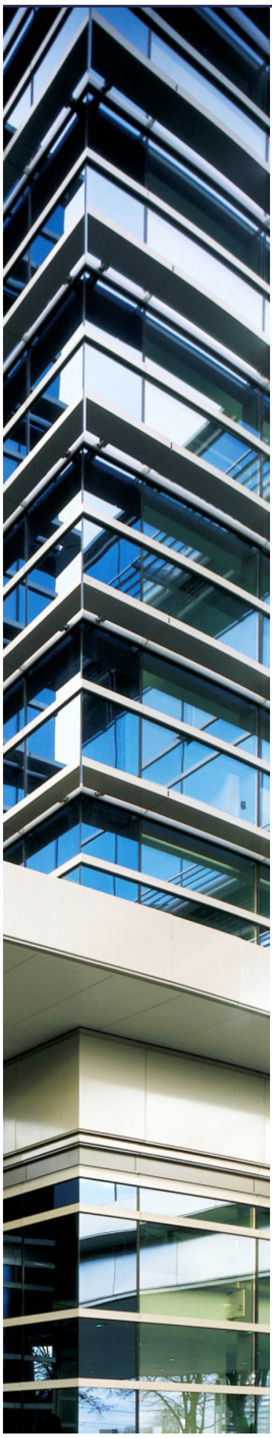

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Financial Intermediation and Climate Change in a Production and Investment Network Model for the Euro Area

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Abstract

This paper introduces financial intermediaries, who engage in lending to firms for investments and buying public bonds issued by the government, and unconventional monetary policy in the form of quantitative easing or tightening into a rich New-Keynesian multi-sector E-DSGE model with production and investment networks. Due to the strong input-output linkages between sectors, almost all policies are found to be not effective in facilitating a green transition. The policies considered are sector-specific bank regulation policies, unconventional monetary policies, various carbon tax revenue recycling schemes, public green capital investment, and sector-specific investment tax/subsidy policies. Only if carbon tax revenues are used to build public green capital, thereby boosting productivity of the green sectors, the trade-off between achieving positive economic growth and reducing carbon emissions is fully resolved.

Keywords: Production network, Investment network, Climate change, Financial intermediation, Financial stability, Stranded assets, Monetary policy

JEL codes: E22, E32, E52, G21, L14, Q50

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1 Introduction

Since the Global Financial Crisis of the late 2000s, shocks that could disrupt financial stability and the policies and tools to address such disruptions have gained importance for both policymakers and researchers. Transition and physical risks which originate from climate change and relevant climate change mitigation or adaption policies are among the most significant factors that could impact financial stability in the future. The literature emphasises that ensuring financial stability is achievable by being prepared before the shock occurs. The risks posed by climate change inherently carry significant uncertainty for the real economy. In addition to this uncertainty, climate change will also have a direct impact on the financial system by increasing damages from physical risks for insurance companies and reducing the performance of loans to firms negatively impacted by environmental regulation, changing consumer habits, or extreme weather events, for example. Therefore, this situation, which policymakers are not fully prepared for and find difficult to define, will challenge the financial system.

In this respect, a novel literature has started to investigate the effects of climate change, classic environmental policies such as carbon taxes and cap-and-trade systems, as well as non-standard financial sector policies to assist with the economic challenges of climate change such as green quantitative easing (QE), brown quantitative tightening (QT), or sector-specific bank regulation policies. Notable contributions to this literature are, for example, Diluiso et al. (2021), Benmir and Roman (2022), Carattini et al. (2023), and Giovanardi et al. (2023).

Another novel literature utilises large multi-sector (E-)DSGE models where each sector needs to buy products from many other sectors as inputs to utilise in its production process. These input-output linkages are measured in the data using input-output matrices and the amount of intermediate inputs constitutes a sizable share relative to the other production inputs (e.g., labour, capital, energy). These sectoral linkages create networks among the sectors so that economic developments in a large sector that buys many inputs from other sectors has considerable consequences for the other sectors as well. Noteworthy studies in this literature are given by, for example, Baqaee and Farhi (2019), Ghassibe (2021), Frankovic (2022), Hinterlang et al. (2022), and Del Negro et al. (2023).

Therefore, in this paper we introduce financial intermediaries and unconventional monetary policy in the form of QE or QT programmes into the rich New-Keynesian multi-sector E-DSGE model with input-output linkages for intermediate goods production and investment that we have developed in Grüning and Kantur (2023), where the 37 sectors are labelled as green or brown following the green EU taxonomy. Additionally, we model the fiscal sector more realistically by adding public green bonds, government expenditure, as well as a fiscal rule in order to provide an analysis of additional fiscal policy interventions not possible in our previous model. To the best of our knowledge, we are the first who introduce financial intermediaries into a network E-DSGE model.

With this model at hand, we can therefore analyse how the input-output linkages affect the pass-through of non-standard climate change policies including sector-specific bank regulation policies and central bank asset purchases or sales to macroeconomic outcomes, environmental dynamics, and financial stability.

The financial sector is modelled along the lines of Gertler and Karadi (2013) where financial intermediaries lend to capital producers for their investment in capital. Additionally, they buy public bonds from the government. The financial intermediaries use deposits from households and their own net worth to finance these loans and public bonds. They are subject to an incentive compatibility constraint with asset-specific absconding rates so that banks in equilibrium will not abscond with a fraction of their assets.

The central bank – in addition to setting the nominal risk-free rate via a standard Taylor rule – can buy financial assets (corporate loans, public bonds) by issuing reserves to provide financial intermediaries with extra liquidity. The modelling of the monetary authority follows Sims and Wu (2021).

The fiscal authority levies taxes on final consumption, on intermediate consumption (intermediate inputs by firms), on labour income, on carbon emissions, and potentially on investments. While the carbon tax revenue is recycled either in the form of a lump-sum transfer to households, investment subsidies to the green sectors, or public green capital investments, the other tax revenues are used to finance (wasteful) public consumption expenditures. The government can also issue public general bonds to finance public consumption expenditures. Furthermore, it can build public green capital by issuing public green bonds that are bought by the financial intermediaries or the central bank.

We aim to provide an in-depth analysis of the effects of various financial and fiscal policies designed to assist with the transition to a low-carbon economy on macroeconomic outcomes, environmental dynamics, and financial stability.

Specifically, we use impulse response functions to study bank regulation policies via absconding rate shocks in green, brown, or all sectors, Green QE and Brown QT programmes as well as a restructuring of the central bank's balance sheet by combining the Green QE and Brown QT programmes, several carbon tax revenue recycling schemes (lump-sum transfer, investment subsidies, or public green capital build-up), green technology innovations (exogenous productivity shocks vs public green capital build-up financed by public green bond issuance), and sector-specific investment tax and subsidy policies (brown investment taxes, green investment subsidies, or a combination of both).

Policies that do not exert a cost for economic growth or even provide increases in overall production while at the same time reduce emissions considerably, which would typically be achieved by an increase in production volumes in sectors with low emission intensities and a decrease in production volumes in carbon intensive sectors, are particularly helpful in facilitating the transition to a greener economy. Evaluating all aforementioned policies with respect to their green transition potential, only one is found to be fully effective in inducing a green transition: using carbon tax revenues to build public green capital. With this carbon tax revenue recycling scheme in place, an increase in the carbon tax rate is expansionary in terms of output and, in the longer run, consumption. Moreover, this scheme induces a significant reduction of carbon emissions due to more abatement efforts. There is some short-run inflationary pressure though. The green investment subsidy recycling scheme comes close to inducing a true green transition. However, aggregate output declines in the medium run after a short-run increase. In terms of emissions, the decline is substantially larger than in the green public capital recycling scenario and similar to the emissions decrease when carbon taxes are transferred in lump-sum manner to the households. The lump-sum transfer is recessionary though.

Another policy that works quite well is providing investment subsidies in the green sectors by increasing labour taxes. Similarly to financing such subsidies by recycling carbon tax revenues, aggregate output increases in the short run but declines in the medium run. Emissions first increase due to higher production levels but then decrease substantially in the medium run due to higher abatement efforts and the reduction of production activities at the same time.

The reason for the failure of the other policies is the tight link between sectors due to the input-output linkages for both production and investment and the presence of financial intermediaries. Due to this, the dynamics of green and brown sectors' outputs behave similarly since without loss of generality an increase in green sectors' production requires also an increase in brown sectors' production due to the increased demand for intermediate inputs from the brown sectors. Moreover, the sector-specific loan interest rates are aligned almost perfectly which reduces the effectiveness of all investment-related policies due to the financial intermediaries taking advantage of the situation and increasing their margins.

Other policies that induce positive aggregate economic growth effects (reducing absconding rates in the green sectors, a Green QE programme, building public green capital by issuing public green bonds) simultaneously lead to an increase in emissions since both green and brown outputs increase in these scenarios due to the aforementioned channels, and this increase in production activity is not accompanied by a significant increase in abatement efforts. The recessionary policies (increasing absconding rates in the brown sectors, a Brown QT programme, brown investment taxes) reduce emissions successfully but at the cost of lower aggregate output.

Regarding financial stability, an absconding rate increase in the brown sectors induces bank leverage to decrease significantly (more financial stability), while the absconding rate decrease in the green sectors leads to a considerable decrease in financial stability. A Green QE programme increases financial stability in the short run and a Brown QT programme reduces financial stability in the short run. Fiscal policies have a generally smaller impact on financial stability or bank leverage. The largest decrease in bank leverage (increase in financial stability) from such policies comes about from carbon tax revenue recycling in the form of providing green investment subsidies while the largest increase in bank leverage (reduction of financial stability) is induced by a green technology shock.

To some extent, the combination of an expansionary absconding rate decrease in the green sectors and a recessionary absconding rate increase in the brown sectors also solves the trade-off between emissions reductions and economic expansions. However, the effects are very small since these combined policies almost cancel out each other exactly. Nevertheless, a small economic expansion in the short run and a small reduction of emissions in the medium to long run is observed in this combined scenario. Due to the large additional investment needs and the increase in loan costs, the fiscal budget-neutral combination of brown investment taxes and green investment subsidies is recessionary. This is in contrast to the results of Grüning and Kantur (2023) where this fiscal policy delivers an economic expansion and an emission reduction, as there are no financial intermediaries in the previous version of our model and thus there is no increase in loan costs that counteracts the effect of this fiscal policy.

Removing the input-output linkages in intermediate goods production and studying the resulting impulse response functions for this model variant reveals that certain investment-related fiscal policies become more successful in inducing a true green transition. Specifically, revenue recycling in the form of green investment subsidies becomes more expansionary in the short to medium run while reducing emissions more than the other carbon tax recycling schemes and similar dynamics emerge now for the introduction of brown investment taxes, green investment subsidies, and the fiscal budget-neutral combination of these investment policies. Removing the financial intermediaries from the model implies a large improvement of the carbon tax revenue recycling strategy that sees the revenues being used for providing investment subsidies to the green sectors in terms of aggregate output, which increases by 5% in the short run. This short-run surge in output implies a short-run surge in emissions, but emissions are reduced substantially in the medium to long run.

Overall, our results demonstrate that input-output linkages and the presence of financial intermediaries are important to consider for the pass-through of economic policies. While the input-output linkages provide for an amplification of effects, they also make sectors co-move much more, which impairs the effectiveness of economic policies targeted to assist with the green transition. The financial sector, including the central bank, and the conditions with which they provide funding to firms can shape the responses of economic quantities to climate change policies in such a network model like ours considerably. With financial intermediaries acting as shock smoothing agents, investment-related fiscal policies feature a lower pass-through to macroeconomic and environmental dynamics.

Literature review. Our main contribution is to study the effects of environmental and bank regulation policies on macroeconomic, environmental, and financial stability, while considering the production and investment networks among sectors. In doing so, we relate to several strands of literature.

One strand of literature investigates the macro-financial impacts of climate policies. The predecessor to this paper (Grüning and Kantur, 2023) focuses mainly on the macroeconomic effects of stranded assets. However, in this paper, we introduce financial intermediaries into the model to shed light on the trade-off between the environmental benefits of climate policies and macro-financial stability. Analysing the interaction between climate risks and financial stability is relatively new compared to examining macroeconomic relationships as discussed in the literature by Battiston et al. (2021). Climate change and the related mitigation or adaption policies are now considered a major financial risk. Javadi and Masum (2021) provide empirical evidence showing that lenders are increasingly recognising climate change as a significant risk factor. The study finds that firms located in areas with higher exposure to climate change face significantly higher spreads on their bank loans. In a different fashion, Liu et al. (2024) investigate the impact of climate risk on financial stability using a panel data set from 53 countries. Their findings demonstrate that climate risk adversely affects financial stability. However, the extent of this impact varies depending on factors such as economic development, financial development, and competition among countries. Acharya et al. (2023) conduct a climate stress test to evaluate the resilience of banks and the financial system. Their analysis reveals that extreme decarbonisation policies could lead to the bankruptcy of high-emission sectors. Similarly, Alessi et al. (2024) use a climate stress test to assess the impact of climate transition risk on banks' balance sheets and find that an additional capital buffer for risk-weighted assets is, on average, required to safeguard the financial system. Dafermos et al. (2018) examine the effects of physical climate risks on financial stability using a stock-flow ecological macroeconomic model. Their findings indicate that climate shocks lead to a decline in firm capital, worsening profitability and liquidity, which in turn increases default rates and threatens financial stability. Additionally, these shocks prompt portfolio reallocation and a decline in corporate bond prices. Consequently, climate-induced financial instability results in reduced credit expansion and lower economic activity. The study also demonstrates that Green QE can mitigate climate-induced financial instability and help limit global warming.

Our focus is particularly aligned with studies by Diluiso et al. (2021), Benmir and Roman (2022), Carattini et al. (2023), and Giovanardi et al. (2023). These papers develop multi-sector E-DSGE models that incorporate both financial frictions and climate policies. Their findings indicate that financial frictions can amplify transition shocks, significantly affecting the economy. Additionally, they examine the implications of these dynamics for central banks and macroprudential policies, highlighting the critical role these institutions play in managing the economic consequences of climate policy transitions. Our work builds on this foundation, further investigating how financial frictions interact with environmental policies within a DSGE framework. Financial frictions in DSGE models with a banking sector have become popular since the Global Financial Crisis of 2008/2009 after the pioneering works of Bernanke et al. (1999) and Gertler and Karadi (2013). In our model, we also explore the effects of central bank green asset purchases (Green QE), drawing parallels to the analyses conducted by Dafermos et al. (2018), Diluiso et al. (2021), and Ferrari and Nispi Landi (2023).

Another related strand of literature focuses on incorporating an environmental component into DSGE models, referred to as E-DSGE models, to analyse climate and environmental policies within business cycles. This approach is exemplified by studies such as Heutel (2012), Annicchiarico and Di Dio (2015), Hinterlang et al. (2023), and Chan and Punzi (2023). In our model we can also investigate the impact of various fiscal policy tools on the economy in the context of a low-carbon transition. Specifically, we analyse how the issuance of public green bonds by the government can facilitate this transition and its effects on macroeconomic and financial stability, as studied by Giovanardi et al. (2023). This approach provides a nuanced understanding of the economic repercussions associated with central banks' and governments' involvement in promoting sustainable investments amid the ongoing shift towards greener economic practices.

Finally, we include input-output linkages and thus a production and investment network structure, similarly modelled as in Baqaee and Farhi (2019) and Ghassibe (2021). Notable E-DSGE models with input-output linkages include Hinterlang et al. (2021), Frankovic (2022), Hinterlang et al. (2022), Ernst et al. (2023), and Del Negro et al. (2023). The studies by Frankovic (2022) and Ernst et al. (2023) utilise multi-country models to explore the international relevance of input-output linkages, while the other aforementioned studies operate in a closed economy framework, as we do.

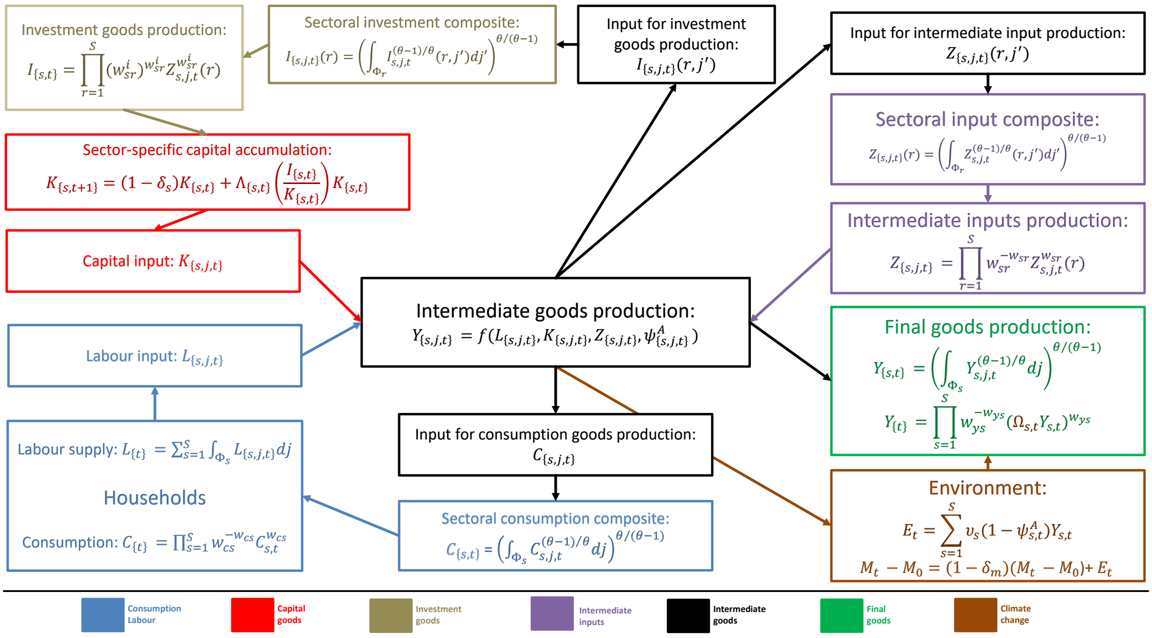
Relative to the reviewed existing modelling literature, our key novelty is the integration of financial intermediaries into a network E-DSGE New-Keynesian model. This allows us to shed light on the economic effects of the presence of input-output linkages and financial intermediaries with respect to carbon tax recycling options, investment subsidy and tax schemes, as well as sector-specific bank regulation and unconventional monetary policies.

In what follows, Section 2 describes our multi-sector production network New-Keynesian model with financial intermediaries, Section 3 gives the details on the calibration of a 37-sector version of our model, and Section 4 is devoted to the analysis of our model. Finally, Section 5 provides concluding remarks. Technical details and additional results are relegated to the appendices.

2 Model

This section develops our multi-sector model with Figure 1 providing a bird's eye view.

Figure 1: Production network structure of the model



Notes: This figure depicts the production network structure in our model.

2.1 Representative household

The representative household consumes goods from all S sectors by means of the following consumption goods aggregate that assumes a unit elasticity of substitution across sectors:

$$C_t = \prod_{s=1}^{S} (\omega_{cs})^{-\omega_{cs}} C_{s,t}^{\omega_{cs}}, \tag{1}$$

where ω_{cs} is the relative weight of consumption for goods produced in sector s ($\sum_{s=1}^{S} \omega_{cs} = 1$) or the proportion of aggregate consumption expenditure $P_t^c C_t$ spent on sector s goods $(1+\tau_{s,t}^c)P_{s,t}C_{s,t}$. This final consumption goods basket is supplied by a perfectly competitive retail firm, owned by the household, which bundles all sectoral goods together and which maximises its profits (in nominal terms), given Equation (1):

$$Z_t^C = \max_{\{C_{s,t}\}_{s=1}^{S}} \left\{ P_t^c C_t - \sum_{s=1}^{S} (1+\tau_{s,t}^c) P_{s,t} C_{s,t} \right\}, \tag{2}$$

so that the consumption of goods from sector s is subject to a proportional consumption tax at rate $\tau^c_{s,t}$. The first order conditions are given by:

$$(1+\tau^c_{s,t})P_{s,t}C_{s,t} = P^c_t \omega_{cs} C_t, \quad s = 1,\ldots,S. \tag{3}$$

The price index of this consumption goods aggregate will be denoted by P^c_t. It satisfies $P^c_t C_t = \sum_{s=1}^{S}(1+\tau^c_{s,t})P_{s,t}C_{s,t}$ and is derived by plugging the first order conditions (3) into the consumption aggregator function (1):

$$P^c_t = \prod_{s=1}^{S} [(1+\tau^c_{s,t})P_{s,t}]^{\omega_{cs}}. \tag{4}$$

The amount of consumption goods by all firms in sector s is determined by bundling together the inputs from all firms in sector s according to:

$$C_{s,t} = \left(\int_{\Phi_s} C_{s,j,t}^{(\theta-1)/\theta}\, dj \right)^{\theta/(\theta-1)}, \tag{5}$$

where Φ_s is the set of all firms in sector s. Moreover, θ is the elasticity of substitution between any goods.

There is a unit mass of households, indexed by $h \in [0,1]$. Each household maximises lifetime utility from consumption minus disutility from labour (β – time discount factor, f – Frisch elasticity of labour supply, χ – leisure utility scaling parameter, ψ – elasticity of intertemporal substitution) by choosing consumption $C_t(h)$, its differentiated labour service $L_{s,t}(h)$ in each sector $s = 1,\ldots,S$, and deposit holdings $D_{t+1}(h)$:

$$U_t = \mathbb{E}_t \left[\sum_{n=0}^{\infty} \frac{\beta^n}{1-1/\psi} \left(C_{t+n}(h) - \frac{\chi \left(\sum_{s=1}^{S} L_{s,t+n}(h) \right)^{1+1/f}}{1+1/f} \right)^{1-1/\psi} \right]. \tag{6}$$

The expenses and incomes of households give rise to the following (nominal) budget constraint for the representative household:

$$\begin{aligned} P^c_t \int_0^1 C_t(h)\, dh + \int_0^1 D_{t+1}(h)\, dh + \mathcal{P}_t \Phi_t &= (1-\tau^W_t) \sum_{s=0}^{S} \int_0^1 W_{s,t} L_{s,t}(h)\, dh + T_t \\ + R^d_{t-1} \int_0^1 D_t(h)\, dh + \sum_{s=1}^{S} (Z^Y_{s,t} + Z^y_{s,t} + Z^k_{s,t}) &+ Z^C_t + Z^Y_t + Z^b_t + (1-\theta)\mathrm{NW}_{t-1}, \end{aligned} \tag{7}$$

where R^d_{t-1} is the nominal interest rate earned at time t on deposits between time $t-1$ and t, Φ_t is the bank start-up funds transferred to new banks by households (in real terms), $\mathcal{P}_t$ is the aggregate price index which will be formally defined in the next section, Z^C_t and

Z_t^Y are the nominal profits of the aggregate consumption goods producer and aggregate final goods producer, respectively, $Z_{s,t}^y$ ($Z_{s,t}^Y$, $Z_{s,t}^k$) is the nominal profit of all intermediate goods firms (sectoral final goods producers, capital producers) in sector s, Z_t^b is the flow of funds transferred by banks to households, $(1-\theta)\mathrm{NW}_{t-1}$ is the net worth of exiting banks, T_t is a lump-sum transfer from the fiscal authority, τ_t^W is the labour income tax rate, and $W_{s,t}$ is the nominal wage in sector s. Solving the resulting Lagrangian (the multiplier attached to the budget constraint is denoted by $\lambda_{h,t}$) results into the following equilibrium conditions:

$$\lambda_{h,t} = \frac{1}{P_t^c}\left(C_t - \frac{\chi(L_t)^{1+1/f}}{1+1/f}\right)^{-1/\psi}, \tag{8}$$

$$1 = \mathbb{E}_t[\mathbb{M}_{t,t+1}^{\$} R_t^d], \tag{9}$$

$$\mathbb{M}_{t,t+1}^{\$} = \beta\frac{\lambda_{h,t+1}}{\lambda_{h,t}}, \tag{10}$$

where $\mathbb{M}_{t,t+1}^{\$}$ is the nominal stochastic discount factor. We define (after-tax) consumer price inflation by:

$$\Pi_{t+1}^c = P_{t+1}^c/P_t^c. \tag{11}$$

The households face sector-specific Calvo-style wage rigidities. The total aggregate labour supply and demand as well as the sectoral labour supplies of the representative household are thus given by the following expressions:

$$L_t = \sum_{s=1}^{S} L_{s,t}, \tag{12}$$

$$L_{s,t} = \left(\int_0^1 (L_{s,t}(h))^{(\theta_{\ell s}-1)/\theta_{\ell s}}\, dh\right)^{\theta_{\ell s}/(\theta_{\ell s}-1)}. \tag{13}$$

The sector-specific union within household sector chooses the labour supply of household h by maximizing the following expression:

$$\max_{\{L_{s,t}^d(h)\}} \left\{W_{s,t}(h)L_{s,t}^d(h) - W_{s,t}L_{s,t}^d\right\}, \tag{14}$$

subject to the sectoral labour market clearing condition: $L_{s,t}^d(h) = L_{s,t}(h)$. The first order condition yields the following labour demand equation:

$$L_{s,t}^d(h) = (W_{s,t}(h)/W_{s,t})^{-\theta_{\ell s}} L_{s,t}^d. \tag{15}$$

Assuming that the sectoral wage cannot be adjusted in a given period with probability $\kappa_{\ell s}$ and the absence of any indexation of the wage to past inflation, the household chooses the optimal wage by solving the following optimisation problem:

$$\max_{\{W_{s,t}(h)\}} \left\{ \mathbb{E}_t \left[\sum_{n=0}^{\infty} (\beta\kappa_{\ell s})^n \left(\lambda_{h,t+n}(1-\tau^W_{t+n}) W_{s,t+n}(h) L^d_{s,t+n}(h) \right.\right.\right.$$
$$\left.\left.\left. + \frac{1}{1-1/\psi} \left(C_{t+s} - \frac{\chi \left(\sum_{s=1}^S L^d_{s,t+n}(h) \right)^{1+1/f}}{1+1/f} \right)^{1-1/\psi} \right) \right] \right\}. \tag{16}$$

Solving this optimisation problem is quite standard and the equilibrium equations for each sector $s = 1, \ldots, S$ are essentially the same as in Schmitt-Grohé and Uribe (2005), after taking account of our assumed utility function and the absence of any wage indexation:

$$g_{s,1,t} = g_{s,2,t}, \tag{17}$$
$$W_{s,t} = \left((1-\kappa_{\ell s})(W^*_{s,t})^{1-\theta_{\ell s}} + \kappa_{\ell s}(W_{s,t-1})^{1-\theta_{\ell s}} \right)^{1/(1-\theta_{\ell s})}, \tag{18}$$
$$L_{s,t} = \Theta^W_{s,t} L^d_{s,t}, \tag{19}$$
$$\Theta^W_{s,t} = (1-\kappa_{\ell s}) \left(\frac{W^*_{s,t}}{W_{s,t}} \right)^{-\theta_{\ell s}} + \kappa_{\ell s} \left(\frac{W_{s,t-1}}{W_{s,t}} \right)^{-\theta_{\ell s}} \Theta^W_{s,t-1}. \tag{20}$$

In the above equations, $\Theta^W_{s,t}$ denotes the wage dispersion process in sector s, $L^d_{s,t}$ is the sectoral labour demand, while $L_{s,t}$ denotes the sectoral labour supply. The variables $g_{s,1,t}$ and $g_{s,2,t}$ are auxiliary variables to determine the optimal sectoral wage $W^*_{s,t}$, which are given in the following recursive forms:

$$g_{s,1,t} = \frac{\theta_{\ell s} \chi \lambda_{h,t} P^c_t}{\theta_{\ell s} - 1} (L^d_t)^{1/f} \left(\frac{W^*_{s,t}}{W_{s,t}} \right)^{-\theta_{\ell s}} L^d_{s,t} + \beta\kappa_{\ell s} \mathbb{E}_t \left[\left(\frac{W^*_{s,t}}{W^*_{s,t+1}} \right)^{-\theta_{\ell s}} g_{s,1,t+1} \right], \tag{21}$$
$$g_{s,2,t} = (1-\tau^W_t) \lambda_{h,t} \left(\frac{W^*_{s,t}}{W_{s,t}} \right)^{-\theta_{\ell s}} W^*_{s,t} L^d_{s,t} + \beta\kappa_{\ell s} \mathbb{E}_t \left[\left(\frac{W^*_{s,t}}{W^*_{s,t+1}} \right)^{1-\theta_{\ell s}} g_{s,2,t+1} \right]. \tag{22}$$

Finally, the aggregate wage W_t obeys:

$$W_t L^d_t = \sum_{s=1}^S W_{s,t} L^d_{s,t}. \tag{23}$$

These equations complete the set of household equilibrium conditions.

2.2 Aggregate final goods firm

There is a representative, perfectly competitive firm that buys all the sectors' final goods and assembles them into an aggregate final good (or GDP) by means of the following production function:

$$Y_t = \prod_{s=1}^S \omega_{ys}^{-\omega_{ys}} (\Omega_{s,t} Y_{s,t})^{\omega_{ys}}, \tag{24}$$

where ω_{ys} refers to the relative weight of the output of sector s in aggregate GDP. The climate damage function $\Omega_{s,t}$ is given by:

$$\Omega_{s,t} = e^{-\iota_{1s} \cdot M_t}, \tag{25}$$

where M_t is the stock of carbon above pre-industrial levels in the atmosphere and ι_{1s} the sensitivity of production to climate change in sector s. Furthermore, the price index of aggregate GDP and aggregate inflation are defined by:

$$\mathcal{P}_t = \prod_{s=1}^{S} \left(\frac{P_{s,t}}{\Omega_{s,t}} \right)^{\omega_{ys}}, \tag{26}$$

$$\Pi_{t+1} = \mathcal{P}_{t+1} / \mathcal{P}_t. \tag{27}$$

The final goods firm solves the following optimisation problem:

$$Z_t^Y = \max_{\{Y_{s,t}\}_{s=1}^{S}} \left\{ \mathcal{P}_t Y_t - \sum_{s=1}^{S} P_{s,t} Y_{s,t} \right\}, \tag{28}$$

which results into the following first order conditions:

$$P_{s,t} Y_{s,t} = \mathcal{P}_t \omega_{ys} Y_t, \quad s = 1, \ldots, S. \tag{29}$$

2.3 Sectoral final goods firms

There are S production sectors, indexed by $s = 1, \ldots, S$. The sector-specific intermediate goods are bundled by final goods firms as follows:

$$Y_{s,t} = \left(\int_{\Phi_s} Y_{s,j,t}^{(\theta-1)/\theta} \, dj \right)^{\theta/(\theta-1)}. \tag{30}$$

The sectoral final goods firms maximise the profits from selling the sectoral goods and purchasing the inputs from all intermediate goods firms, given by the following expression, by choosing intermediate inputs $Y_{s,j,t}$, subject to Equation (30):

$$Z_{s,t}^Y = \max_{\{Y_{s,j,t}\}_{j \in \Phi_s}} \left\{ P_{s,t} Y_{s,t} - \int_{\Phi_s} P_{s,j,t} Y_{s,j,t} \, dj \right\}. \tag{31}$$

The resulting first order conditions are:

$$P_{s,j,t} = P_{s,t} \left(\frac{Y_{s,t}}{Y_{s,j,t}} \right)^{1/\theta}, \quad s = 1, \ldots, S. \tag{32}$$

2.4 Intermediate goods firms

The production function of firm j in sector s is specified as follows:

$$Y_{s,j,t} = (1 + K^p_{g,t})^{\alpha_{gs}} A_{s,t} \left(\zeta_s (\text{VA}_{s,j,t})^{(\sigma_s-1)/\sigma_s} + (1-\zeta_s)(Z_{s,j,t})^{(\sigma_s-1)/\sigma_s}\right)^{\sigma_s/(\sigma_s-1)}, \quad (33)$$

$$\text{VA}_{s,j,t} = \left(\alpha_s (u_{s,t} K_{s,j,t})^{(\gamma_s-1)/\gamma_s} + (1-\alpha_s)(L_{s,j,t})^{(\gamma_s-1)/\gamma_s}\right)^{\gamma_s/(\gamma_s-1)}, \quad (34)$$

where value-added $\text{VA}_{s,j,t}$ is a constant-elasticity-of-substitution (CES) bundle of labour $L_{s,j,t}$ with weight $1-\alpha_s$ and utilised capital $u_{s,t}K_{s,j,t}$ with elasticity of substitution denoted by γ_s. For the production of intermediate goods, value-added and intermediate inputs are bundled together with elasticity of substitution denoted by σ_s and the weight on value-added by ζ_s. The variable $K^p_{g,t}$ is green public capital built by the government and α_{gs} determines the extra production amount that green public capital induces in each sector. We will assume that this parameter is zero in all brown sectors and positive in all green sectors to make the public capital stock a green one. The utilisation rate and total factor productivity in sector s are specified by the following exogenous processes:

$$\ln(u_{s,t}) = (1-\rho_u)\ln(\bar{u}_s) + \rho_u \ln(u_{s,t-1}) + \sigma_u \varepsilon_{s,u,t}, \quad s = 1, \dots, S, \quad (35)$$

$$\ln(A_{s,t}) = (1-\rho_a)\bar{a} + \rho_a \ln(A_{s,t-1}) + \sigma_a \varepsilon_{a,s,t}, \quad s = 1, \dots, S, \quad (36)$$

where $\bar{a}$ is the log steady-state total factor productivity or technology in all sectors. The total amount of intermediate inputs in sector s used by firm j is given by:

$$Z_{s,j,t} = \prod_{r=1}^{S} (\omega_{sr})^{-\omega_{sr}} Z^{\omega_{sr}}_{s,j,t}(r), \quad (37)$$

where ω_{sr} is the relative intensity with which sector s firms use goods from sector r as inputs ($\sum_{r=1}^{S} \omega_{sr} = 1$), implying a unit elasticity of substitution between inputs from different sectors. The parameter ω_{sr} is the (s, r) entry of the input-output matrix. The amount of intermediate inputs from sector r used by sector s firm j is given by the following aggregator:

$$Z_{s,j,t}(r) = \left(\int_{\Phi_r} Z_{s,j,t}(r, j')^{(\theta-1)/\theta}\, dj'\right)^{\theta/(\theta-1)}. \quad (38)$$

It is assumed that $\theta > 1$ so that it is harder to substitute inputs across sectors than within a particular sector. The intermediate input firm minimises the total expenditure on buying the inputs to assemble the bundle $Z_{s,j,t}(r)$, where P^s_t is the intermediate inputs price index of sector s and $P_{r,t}$ the sectoral price index of sector r:

$$P_t^s = \prod_{r=1}^{S} (P_{r,t})^{\omega_{sr}}, \quad s = 1, \dots, S, \tag{39}$$

$$P_{r,t} = \left(\int_{\Phi_r} P_{r,j',t}^{1-\theta}\, dj' \right)^{1/(1-\theta)}, \quad r = 1, \dots, S. \tag{40}$$

Therefore, the cost minimisation problem of the intermediate input firm j in sector s, subject to the aggregator function (37), is given by:

$$\min_{\{Z_{s,j,t}(r)\}_{r=1}^{S}} \left\{ \sum_{r=1}^{S} P_{r,t} Z_{s,j,t}(r) - P_t^s Z_{s,j,t} \right\}. \tag{41}$$

The resulting optimisation problems' solution is given by the following first order conditions (after imposing firm symmetry):

$$P_{r,t} Z_{s,t}(r) = P_t^s \omega_{sr} Z_{s,t}, \quad r = 1, \dots, S, \quad s = 1, \dots, S. \tag{42}$$

The symmetric decisions of firms also imply (via Equation 37):

$$Z_{s,t} = \prod_{r=1}^{S} (\omega_{sr})^{-\omega_{sr}} Z_{s,t}^{\omega_{sr}}(r), \quad s = 1, \dots, S. \tag{43}$$

Using the first order condition (42) in the aggregator function (43) implies the functional form of the intermediate input price index in Equation (39), which satisfies $P_t^s Z_{s,t} = \sum_{r=1}^{S} P_{r,t} Z_{s,t}(r)$. The intermediate goods firm j in sector s chooses labour input $L_{s,j,t}^d$, capital input $K_{s,j,t}$, intermediate input bundle $Z_{s,j,t}$, and the carbon abatement rate, subject to the production function (33) (Lagrange multiplier $\mathrm{MC}_{j,t}$), by minimising the following expression for total costs:

$$W_{s,t} L_{s,j,t}^d + R_{s,t}^k K_{s,j,t} + (1+\tau_{s,t}^z) P_t^s Z_{s,j,t} + \mathcal{P}_t \tau_{s,t}^F \nu_s (1-\psi_{s,j,t}^A) Y_{s,j,t} + P_{s,t} X_{s,j,t}^A - \mathrm{MC}_{s,j,t} Y_{s,j,t}, \tag{44}$$

where $\tau_{s,t}^F$ is the sector-specific real carbon tax rate, ν_s is the sector-specific carbon intensity, and abatement investment in sector s by firm j is given by:

$$X_{s,j,t}^A = \iota_{2s} (\psi_{s,t}^A)^{\iota_{3s}} Y_{s,j,t}. \tag{45}$$

Additionally, $\mathrm{MC}_{s,j,t}$ is the nominal marginal cost of firm j in sector s, and $R_{s,t}^k$ the rental rate of capital in sector s. The first order conditions from the cost minimisation problems for $s = 1, \dots, S$ are given by:[1]

[1]After assuming that in each sector all firms choose the same capital-labour ratio and thus take the same decisions except for abatement rates – consequently, also the carbon tax burden is specific to the

$$W_{s,t} = \mathrm{MC}_{s,t}(Y_{s,t})^{1/\sigma_s}(A_{s,t}(1+K_{g,t}^p)^{\alpha_{gs}}))^{1-\sigma_s}\zeta_s(\mathrm{VA}_{s,t})^{1/\gamma_s-1/\sigma_s}(1-\alpha_s)(L_{s,t}^d)^{-1/\gamma_s}, \tag{46}$$

$$(1+\tau_{s,t}^z)P_t^s = \mathrm{MC}_{s,t}(Y_{s,t})^{1/\sigma_s}(A_{s,t}(1+K_{g,t}^p)^{\alpha_{gs}}))^{1-\sigma_s}(1-\zeta_s)(Z_{s,t})^{-1/\gamma_s}, \tag{47}$$

$$R_{s,t}^k = \mathrm{MC}_{s,t}(Y_{s,t})^{1/\sigma_s}(A_{s,t}(1+K_{g,t}^p)^{\alpha_{gs}}))^{1-\sigma_s}\zeta_s(\mathrm{VA}_{s,t})^{1/\gamma_s-1/\sigma_s}\alpha_s(u_{s,t}K_{s,t})^{-1/\gamma_s}u_{s,t}, \tag{48}$$

$$\psi_{s,j,t}^A = \left(\frac{\tau_{s,t}^F\mathcal{P}_t}{P_{s,t}}\frac{\nu_s}{\iota_{2s}\iota_{3s}}\right)^{1/(\iota_{3s}-1)}. \tag{49}$$

Marginal cost of firm j depends on the firm-specific abatement rate and carbon tax burden in the following way:

$$\mathrm{MC}_{s,j,t} = \mathrm{MC}_{s,t} + \mathcal{P}_t\tau_{s,t}^F\nu_s(1-\psi_{s,j,t}^A) + P_{s,t}\iota_{2s}(\psi_{s,j,t}^A)^{\iota_{3s}}, \tag{50}$$

where $\mathrm{MC}_{j,t}$ is the component in marginal costs attached to the same capital-labour ratio that firms in each sector choose. This approach of accounting for carbon taxes and abatement effort in the price-setting problem follows Benmir and Roman (2022). The nominal profits earned by all intermediate goods firms in sector s are given by:

$$Z_{s,t}^y = \int_{\Phi_s}\left(P_{s,j,t}Y_{s,j,t} - W_{s,t}L_{s,j,t}^d - R_{s,t}^kK_{s,j,t} - (1+\tau_{s,t}^z)P_t^sZ_{s,j,t} - \mathcal{P}_t\tau_{s,t}^F\nu_s(1-\psi_{s,j,t}^A)Y_{s,j,t} - P_{s,t}X_{s,j,t}^A\right)dj. \tag{51}$$

Price stickiness in the intermediate goods sector is modelled via introducing Calvo-type price stickiness where the prices can adjust in sector s according to the sector-specific probability $1-\kappa_s$. The optimal nominal price at time t for sector s is denoted by $P_{s,t}^*$, which is equal to $P_{s,j,t}$ with index j in the set of firms that are allowed to re-optimise in what follows, and $\Pi_{t,t+k} = \mathcal{P}_{t+k}/\mathcal{P}_t$ denotes inflation between time $t+k$ and time t. We assume that there is no indexing of prices to inflation so that $P_{s,j,t+k} = P_{s,j,t}$ for those firms with index j in the set of firms that cannot re-optimise in all periods between time t and time $t+k$. With this optimal price and Equation (40), the sectoral price index is found to be:

$$P_{s,t} = \left[\kappa_sP_{s,t-1}^{1-\theta} + (1-\kappa_s)(P_{s,t}^*)^{1-\theta}\right]^{1/(1-\theta)}, \quad s = 1,\ldots,S. \tag{52}$$

The optimal price setting problem is given by:

$$\max_{\{P_{s,j,t}\}}\left\{\mathbb{E}_t\left[\sum_{i=0}^{\infty}\kappa_s^i\mathbb{M}_{t,t+i}\left(\frac{P_{s,j,t+i}Y_{s,j,t+i} - \mathrm{MC}_{s,t+i}Y_{s,j,t+i}}{\mathcal{P}_{t+i}}\right)\right]\right\}, \tag{53}$$

firm – which implies symmetry and being able to drop the firm index j in the first three first order conditions.

subject to first order conditions (29) and (32). Combining these two first order conditions yields:

$$P_{s,j,t} = \frac{\mathcal{P}_t \omega_{ys} Y_t}{Y_{s,t}} \left(\frac{Y_{s,t}}{Y_{s,j,t}} \right)^{1/\theta}, \quad s = 1, \dots, S. \tag{54}$$

After substituting in the just derived equation into the optimisation problem, one obtains:

$$\max_{\{P_{s,j,t}\}} \left\{ \mathbb{E}_t \left[\sum_{i=0}^{\infty} \frac{\kappa_s^i \mathbb{M}_{t,t+i} Y_{s,t+i}^{1-\theta}}{(\omega_{ys} Y_{t+i})^{-\theta}} \left(\left(\frac{P_{s,j,t+i}}{\mathcal{P}_{t+i}} \right)^{1-\theta} - \frac{\mathrm{MC}_{s,j,t+i}}{\mathcal{P}_{t+i}} \left(\frac{P_{s,j,t+i}}{\mathcal{P}_{t+i}} \right)^{-\theta} \right) \right] \right\}, \tag{55}$$

which results into the following first order conditions ($s = 1, \dots, S$) after a couple of standard derivations and using the assumption of no indexation of rigid prices:

$$0 = \mathbb{E}_t \left[\sum_{i=0}^{\infty} \kappa_s^i \mathbb{M}_{t,t+i} Y_{s,t+i} \left(\frac{Y_{s,t+i}}{Y_{t+i}} \right)^{-\theta} (\Pi_{t,t+i})^{\theta-1} \left(\frac{P_{s,t}^*}{\mathcal{P}_t} - \frac{\theta \mathrm{mc}_{s,j,t+i} \Pi_{t,t+i}}{\theta - 1} \right) \right], \tag{56}$$

where $\mathrm{mc}_{s,j,t+i} = \mathrm{MC}_{s,j,t+i}/\mathcal{P}_{t+i}$ is the sector s-specific real marginal cost. These first order conditions can be expressed in the symmetric equilibrium (where all firms within a sector also choose the same abatement effort) by:

$$\frac{P_{s,t}^*}{\mathcal{P}_t} = \frac{f_{1,s,t} + f_{3,s,t}}{f_{2,s,t}}, \quad s = 1, \dots, S, \tag{57}$$

where the variables $f_{1,s,t}$, $f_{2,s,t}$, and $f_{3,s,t}$ are recursively defined as follows:

$$f_{1,s,t} = \mu \left(\frac{Y_{s,t}}{\omega_{ys} Y_t} \right)^{-\theta} \mathrm{mc}_{s,t} Y_{s,t} + \kappa_s \mathbb{E}_t[\mathbb{M}_{t,t+1} (\Pi_{t+1})^{\theta} f_{1,s,t+1}], \tag{58}$$

$$f_{2,s,t} = \left(\frac{Y_{s,t}}{\omega_{ys} Y_t} \right)^{-\theta} Y_{s,t} + \kappa_s \mathbb{E}_t[\mathbb{M}_{t,t+1} (\Pi_{t+1})^{\theta-1} f_{2,s,t+1}], \tag{59}$$

$$f_{3,s,t} = \mu \left(\frac{Y_{s,t}}{\omega_{ys} Y_t} \right)^{-\theta} \left(\frac{P_{s,t}}{\mathcal{P}_t} \iota_{2s} (\psi_{s,t}^A)^{\iota_{3s}} + \tau_{s,t}^F \nu_s (1 - \psi_{s,t}^A) \right) Y_{s,t} + \kappa_s \mathbb{E}_t[\mathbb{M}_{t,t+1} (\Pi_{t+1})^{\theta} f_{3,s,t+1}], \tag{60}$$

where $\mu := \theta/(\theta - 1)$ is the intermediate goods producers' monopoly markup over marginal cost and $\Pi_{t+1} = \Pi_{t,t+1}$. Due to firm symmetry and the equilibrium price setting distortion, the final goods output of sector s is determined by the following equation:

$$\mathring{Y}_{s,t} = Y_{s,t}/\mathring{P}_{s,t} = (\mathring{P}_{s,t})^{-1} (1 + K_{g,t}^p)^{\alpha_{gs}} A_{s,t} \left(\zeta_s (\mathrm{VA}_{s,t})^{(\sigma_s - 1)/\sigma_s} + (1 - \zeta_s)(Z_{s,t})^{(\sigma_s - 1)/\sigma_s} \right)^{\sigma_s/(\sigma_s - 1)}, \tag{61}$$

where the price distortion variable $\mathring{P}_{s,t}$ obeys the following law of motion (see Appendix A for the derivation):

$$\mathring{P}_{s,t} = \kappa_s \left(P_{s,t}/P_{s,t-1} \right)^{\theta} \mathring{P}_{s,t-1} + (1 - \kappa_s) \left(P_{s,t}^*/P_{s,t} \right)^{-\theta}, \quad s = 1, \dots, S. \tag{62}$$

2.5 Capital producers

Sectoral capital is produced by a representative perfectly competitive sectoral capital producer, where capital accumulates according to:

$$K_{s,t+1} = (1-\delta_s)K_{s,t} + \Lambda_s(I_{s,t}/K_{s,t})K_{s,t}, \quad s = 1,\dots,S. \tag{63}$$

where $\Lambda_s(\cdot)$ is the sector-specific capital adjustment cost function. These functions are specified as follows:

$$\Lambda_{s,t} = \Lambda_s(I_{s,t}/K_{s,t}) = \frac{\alpha_{1s}\cdot(I_{s,t}/K_{s,t})^{1-1/\xi_s}}{1-1/\xi_s} + \alpha_{2s}, \quad s = 1,\dots,S, \tag{64}$$

where ξ_s is the capital adjustment costs elasticity and the constants α_{1s} and α_{2gs} in each sector s are chosen such that there are no adjustment costs in any sector in the deterministic steady state. Finally, δ_s is the capital depreciation rate in sector s. The investment goods are bundled together from the intermediate goods output of individual firms in each sector as follows:

$$I_{s,t} = \prod_{r=1}^{S}(\omega^i_{sr})^{-\omega^i_{sr}}(I_{s,t}(r))^{\omega^i_{sr}}, \tag{65}$$

where ω^i_{sr} is the relative intensity with which sector s capital producers use goods from sector r as inputs ($\sum_{r=1}^{S}\omega^i_{sr} = 1$), implying a unit elasticity of substitution between inputs from different sectors. The parameter ω^i_{sr} is the (s,r) entry of the investment input-output matrix. The amount of investment goods from sector r used by sector s is given by the following aggregator:

$$I_{s,t}(r) = \left(\int_{\Phi_r} I_{s,t}(r,j)^{(\theta-1)/\theta}\,dj\right)^{\theta/(\theta-1)}. \tag{66}$$

The investment good producer minimises the total expenditure on buying the inputs to assemble the bundle $I_{s,t}(r)$, where $P^i_{s,t}$ is the investment good price index of sector s and $P_{r,t}$ the sectoral price index of sector r:

$$P^i_{s,t} = \prod_{r=1}^{S}(P_{r,t})^{\omega^i_{sr}}, \quad s = 1,\dots,S. \tag{67}$$

Therefore, the cost minimisation problem of the investment good producers in sector s, subject to the aggregator function (65), is given by:

$$\min_{\{I_{s,t}(r)\}_{r=1}^{S}} \left\{\sum_{r=1}^{S} P_{r,t}I_{s,t}(r) - P^i_{s,t}I_{s,t}\right\}. \tag{68}$$

The resulting optimisation problems' solution is given by the following first order conditions (after imposing firm symmetry):

$$P_{r,t} I_{s,t}(r) = P^i_{s,t} \omega^i_{sr} I_{s,t}, \quad r = 1, \ldots, S, \quad s = 1, \ldots, S. \tag{69}$$

Maximizing values of profits of renting out capital (or the cum-dividend stock price of the green and brown capital producers) is done by choosing the aggregate investment demands and next period's aggregate capital stock demands in sector s in the following objective functions, subject to the capital accumulation equations (63) with Lagrange multiplier $Q_{s,t+n}\mathbb{M}^{\$}_{t,t+n}$:

$$V^k_{s,t} = \max_{\{I_{s,t}; K_{s,t+1}; L^i_{s,t+1}\}} \left\{ \mathbb{E}_t \left[\sum_{n=0}^{\infty} \mathbb{M}^{\$}_{t,t+n} \left(R^k_{s,t+n} K_{s,t+n} - (1+\tau^i_{s,t}) P^i_{s,t+n} I_{s,t+n} + L^i_{s,t+n+1} - R^i_{s,t+n-1} L^i_{s,t+n} \right) \right] \right\}, \tag{70}$$

from which we can read off the capital producers' profit definitions as follows:

$$Z^k_{s,t} = R^k_{s,t} K_{s,t} - (1+\tau^i_{s,t}) P^i_{s,t} I_{s,t} + L^i_{s,t+1} - R^i_{s,t-1} L^i_{s,t}, \quad s = 1, \ldots, S. \tag{71}$$

The optimisation problem is subject to a loan-in-advance constraint of the following type:

$$L^i_{s,t+1} \geq \chi_s (1+\tau^i_{s,t}) P^i_{s,t} I_{s,t}, \quad s = 1, \ldots, S. \tag{72}$$

The parameter χ_s measures the fraction of investment expenditures (net of taxes) that needs to be financed by loans in sector s. Solving this optimisation problem implies the following equilibrium conditions (for $s = 1, \ldots, S$), where the Lagrange multiplier attached to the loan-in-advance constraint is denoted by $\mu^{\mathtt{LIA}}_{s,t}$:

$$Q_{s,t} = (1 + \mu^{\mathtt{LIA}}_{s,t} \chi_s)(1+\tau^i_{s,t}) P^i_{s,t} / \Lambda'_{s,t}, \tag{73}$$

$$Q_{s,t} = \mathbb{E}_t \left[\mathbb{M}^{\$}_{t,t+1} \left(R^k_{s,t+1} - \frac{Q_{s,t+1} \Lambda'_{s,t+1} I_{s,t+1}}{K_{s,t+1}} + Q_{s,t+1}(\Lambda_{s,t+1} + 1 - \delta_s) \right) \right], \tag{74}$$

$$1 + \mu^{\mathtt{LIA}}_{s,t} = \mathbf{E}_t[\mathbf{M}^{\$}_{t,t+1} R^i_{s,t}] = \mathbf{E}_t[\mathbf{M}_{t,t+1} R^i_{s,t} / \Pi_{t+1}] = \mathbf{E}_t[\mathbf{M}_{t,t+1} r^i_{s,t+1}], \tag{75}$$

where the derivative of the capital adjustment cost function is given by:

$$\Lambda'_{s,t} = \alpha_{1s} \cdot (I_{s,t}/K_{s,t})^{-1/\xi_s}, \tag{76}$$

and $\tau^i_{s,t}$ is the tax rate applied to investing in capital in sector s. Note that negative tax rates are equivalent to subsidies.

2.6 Banks

The financial sector is composed of a continuum of banks, indexed by j, with mass 1. The banks originate loans to the capital producers, buy public general and green bonds from the government, and hold central bank reserves. They finance these loans by taking deposits from the households and using their own net worth. Therefore, the balance sheet of an individual bank obeys:

$$\mathrm{NW}_{j,t} + D_{j,t+1} = \mathrm{RE}_{j,t+1} + B^p_{b,j,t+1} + B^p_{g,j,t+1} + \sum_{s=1}^{S} L^{i,p}_{s,j,t+1}, \tag{77}$$

while the nominal net worth of individual bank j evolves as follows:

$$\mathrm{NW}_{j,t} = i_{t-1}\mathrm{RE}_{j,t} + R^b_{b,t-1}B^p_{b,j,t} + R^b_{g,t-1}B^p_{g,j,t} + \sum_{s=1}^{S} R^i_{s,j,t-1}L^{i,p}_{s,j,t} - R^d_{t-1}D_{j,t}. \tag{78}$$

The value of an individual bank $V_{j,t}(\mathrm{NW}_{j,t})$ is conjectured to satisfy $V_{j,t}(\mathrm{NW}_{j,t}) = v_t\mathrm{NW}_{j,t}$. Since we assume that a fixed proportion $\theta_b \in (0,1)$ of banks has to exit every period the Bellman equation for the value of individual bank j is given by:

$$V_{j,t}(\mathrm{NW}_{j,t}) = v_t\mathrm{NW}_{j,t} = \mathbf{E}_t[(1-\theta_b)\mathbf{M}^{\$}_{t,t+1}\mathrm{NW}_{j,t+1} + \theta_b\mathbf{M}^{\$}_{t,t+1}V_{t+1}\mathrm{NW}_{j,t+1}]. \tag{79}$$

The banks maximise their value that is defined via above Bellman equation by choosing bank net worth $\mathrm{NW}_{j,t}$, the amount of public general bonds $B^p_{b,j,t+1}$, the amount of public green bonds $B^p_{g,j,t+1}$, and the amount of loans $L^{i,p}_{s,j,t+1}$ in each sector $s = 1, \ldots, S$, subject to the following incentive compatibility constraint so that banks in equilibrium will not abscond away with a fraction of the assets under their management, which is assumed to be the relevant financial friction in our economy:

$$v_t \cdot \mathrm{NW}_{j,t} \geq \Delta_{bb}B^p_{b,j,t+1} + \Delta_{bg}B^p_{g,j,t+1} + \sum_{s=1}^{S} \Delta_{s,t}L^{i,p}_{s,j,t+1}, \tag{80}$$

where $\Delta_{s,t}$ denotes the sector-specific stringency for corporate loans of this financial friction. Similarly, Δ_{bb} and Δ_{bg} are the absconding rates of public general bonds and public green bonds, respectively. Solving this optimisation problem gives rise to the following first order conditions (denoting by $\mu^{\mathtt{icc}}_{j,t}$ the Lagrange multiplier attached to the incentive compatibility constraint for bank j):[2]

[2]Note that these equilibrium conditions are the same for each bank; therefore, bank symmetry has already been imposed for the displayed equilibrium conditions.

$$(1-\mu_t^{\texttt{icc}})v_t = \mathbf{E}_t[\mathbf{M}_{t,t+1}^{\$}\Omega_{t+1}R_t^d] = \mathbf{E}_t[\mathbf{M}_{t,t+1}\Omega_{t+1}r_{t+1}^d], \tag{81}$$
$$\mu_t^{\texttt{icc}}\Delta_{s,t} = \mathbf{E}_t[\mathbf{M}_{t,t+1}^{\$}\Omega_{t+1}(R_{s,t}^i - R_t^d)] = \mathbf{E}_t[\mathbf{M}_{t,t+1}\Omega_{t+1}(r_{s,t+1}^i - r_{t+1}^d)], \quad s = 1,\ldots,S, \tag{82}$$
$$\mu_t^{\texttt{icc}}\Delta_{bb} = \mathbf{E}_t[\mathbf{M}_{t,t+1}^{\$}\Omega_{t+1}(R_{b,t}^b - R_t^d)] = \mathbf{E}_t[\mathbf{M}_{t,t+1}\Omega_{t+1}(r_{b,t+1}^b - r_{t+1}^d)], \tag{83}$$
$$\mu_t^{\texttt{icc}}\Delta_{bg} = \mathbf{E}_t[\mathbf{M}_{t,t+1}^{\$}\Omega_{t+1}(R_{g,t}^b - R_t^d)] = \mathbf{E}_t[\mathbf{M}_{t,t+1}\Omega_{t+1}(r_{g,t+1}^b - r_{t+1}^d)], \tag{84}$$

where Ω_t, the modification to the household stochastic discount factor for banks, obeys:

$$\Omega_{t+1} = 1 - \theta_b + \theta_b \cdot v_{t+1}. \tag{85}$$

In order to keep the mass of banks equal to 1 across periods, new banks enter to replace the exited banks with mass θ_b. These new banks obtain the start-up funds from households in the nominal amount of $\mathcal{P}_t\Phi_t$. Therefore, the aggregate net worth of the banking sector obeys the following law of motion:

$$\begin{aligned}\mathrm{NW}_t = \theta_b \Bigg(& \frac{\sum_{s=1}^{S}(R_{s,t-1}^i - R_{t-1}^d)L_{s,t}^{i,p}}{\mathrm{NW}_{t-1}} + \frac{(R_{b,t-1}^b - R_{t-1}^d)B_{b,t}^p + (R_{g,t-1}^b - R_{t-1}^d)B_{g,t}^p + (i_{t-1} - R_{t-1}^d)\mathrm{RE}_t}{\mathrm{NW}_{t-1}} \\ & + R_t^d \Bigg) \mathrm{NW}_{t-1} + \mathcal{P}_{t-1}\Phi_{t-1}.\end{aligned} \tag{86}$$

With these assumptions and first order conditions, we can find the nominal flow of funds from banks that are transferred to households to be given by:

$$\begin{aligned}Z_t^b = & \sum_{s=1}^{S}(R_{s,t-1}^i L_{s,t}^{i,p} - L_{s,t+1}^{i,p}) + R_{b,t-1}^b B_{b,t}^p - B_{b,t+1}^p + R_{g,t-1}^b B_{g,t}^p - B_{g,t+1}^p + i_{t-1}\mathrm{RE}_t - \mathrm{RE}_{t+1} \\ & + D_{t+1} - R_{t-1}^d D_t + \mathcal{P}_t\Phi_t - (1-\theta)\mathrm{NW}_{t-1},\end{aligned} \tag{87}$$

where the bank start-up fund is assumed to be a fixed percentage of aggregate bank net worth as follows:

$$\mathcal{P}_t\Phi_t = \varphi \cdot \mathrm{NW}_t. \tag{88}$$

Finally, the sector-specific absconding rates obey the following laws of motion:

$$\Delta_{s,t} = (1-\rho_\Delta)\bar{\Delta}_s + \rho_\Delta\Delta_{s,t-1} + \sigma_\Delta\varepsilon_{\Delta,s,t}, \quad s = 1,\ldots,S. \tag{89}$$

2.7 Monetary authority

The monetary authority applies a classic nominal interest rate rule of the following form to stabilise the deviation of inflation from target and the output gap:

$$\ln(i_t) = (1-\rho_i)\ln(\bar{i}) + \rho_i\ln(i_{t-1}) + (1-\rho_i)\left[\phi_\pi(\ln(\Pi_t) - \ln(\bar{\Pi})) + \phi_y(\ln(Y_t) - \ln(Y))\right] + \sigma_i\varepsilon_{i,t}, \tag{90}$$
$$r_t = i_{t-1}/\Pi_t, \tag{91}$$
$$R_t^d = i_t, \tag{92}$$

where the second equality defines the real risk-free interest rate, $\bar{\Pi}$ is the inflation target or steady-state inflation, and Y is steady-state aggregate final goods output, while the third equality establishes that the nominal cost of deposits for banks (i.e. the deposit interest rate) is equal to the nominal monetary policy rate.

Additionally, the monetary authority can engage in corporate and public bond purchases (quantitative easing) by issuing reserves held by the private banks and investing these reserves in corporate loans in sector s in the amount of $L_{s,t}^{i,cb}$, in public general bonds in the amount of $B_{b,t}^{cb}$, or in public green bonds in the amount of $B_{g,t}^{cb}$ that yields the following balance sheet of the monetary authority:

$$\mathrm{RE}_t = B_{b,t}^{cb} + B_{g,t}^{cb} + \sum_{s=1}^{S} L_{s,t}^{i,cb}. \tag{93}$$

The bond purchases are governed by the equations:

$$B_{b,t}^{cb} = s_{b,t}^{cb} B_{b,t}, \quad s_{b,t}^{cb} = (1-\rho_{cb})\bar{s}_b^{cb} + \rho_{cb} s_{b,t-1}^{cb} + \sigma_{cb}\varepsilon_{b,t}^{cb}, \tag{94}$$

$$B_{g,t}^{cb} = s_{g,t}^{cb} B_{g,t}, \quad s_{g,t}^{cb} = (1-\rho_{cb})\bar{s}_g^{cb} + \rho_{cb} s_{g,t-1}^{cb} + \sigma_{cb}\varepsilon_{g,t}^{cb}, \tag{95}$$

$$L_{s,t}^{i,cb} = s_{\ell,s,t}^{cb} L_{s,t}^{i}, \quad s_{\ell,s,t}^{cb} = (1-\rho_{cb})\bar{s}_{\ell,s}^{cb} + \rho_{cb} s_{\ell,s,t-1}^{cb} + \sigma_{cb}\varepsilon_{\ell,s,t}^{cb}, \quad s = 1,\ldots,S. \tag{96}$$

Finally, the monetary authority transfers all the proceeds from its bond portfolio minus its financing costs (i.e. the central bank profits) to the fiscal authority which implies that the variable $T_{cb,t}$ obeys:

$$T_{cb,t} = R_{b,t-1}^{b} B_{b,t}^{cb} + R_{g,t-1}^{b} B_{g,t}^{cb} + \sum_{s=1}^{S}(R_{s,t-1}^{i} L_{s,t}^{i,cb}) - i_{t-1}\mathrm{RE}_t. \tag{97}$$

2.8 Fiscal authority and environmental dynamics

The fiscal authority collects the tax revenues from taxing carbon emissions by the intermediate goods firms and the deposit adjustment costs from the households. It distributes these revenues in a lump-sum fashion back to the households:

$$T_t = \sum_{s=1}^{S}\left[\tau_{s,t}^{F}\nu_s(1-\psi_{s,t}^{A})\mathring{Y}_{s,t}\right]. \tag{98}$$

Additionally, the fiscal authority collects the tax revenues from taxing the labour income of households, the final consumption of goods by the households, the consumption of intermediate inputs by the intermediate goods producers, and investments by the capital producers. It also receives the transfer from the monetary authority and can issue public general and green bonds. With these tax revenues it finances wasteful public consumption expenditure and the interest payments on its issued bonds, giving rise to the following government budget constraint:

$$R^b_{b,t-1}B_{b,t} + R^b_{g,t-1}B_{g,t} + \sum_{s=1}^{S} G_{s,t} = T_{cb,t} + B_{b,t+1} + B_{g,t+1} \tag{99}$$
$$+ \tau^W_t \sum_{s=1}^{S} W_{s,t}L^d_{s,t} + \sum_{s=1}^{S} \left[\tau^c_{s,t}P_{s,t}C_{s,t} + \tau^i_{s,t}P^i_{s,t}I_{s,t} + \tau^z_{s,t}P^s_t Z_{s,t}\right].$$

The following fiscal rule ensure the stationarity of the debt to GDP ratio (where $b_{b,t}$ is real public general bond holdings):

$$\frac{b_{b,t+1}}{Y_t} = \rho_{by} \cdot \frac{b_{b,t}}{Y_{t-1}} + \phi_{by} \cdot (Y - Y_t). \tag{100}$$

To ensure that this equation holds in equilibrium, the labour income tax rate adjusts endogenously. The government can also issue public green bonds $B_{g,t}$ that are used to build green public capital. The issuance of public green bonds follows an exogenous process that determines that the issuance amount (equal to the public green investment expenditure) is equal to a fraction of aggregate investment expenditure $s^b_{g,t}$ (where $b_{g,t}$ is real public green bond holdings):

$$B_{g,t+1} = s^b_{g,t}P^i_t I_t, \quad s^b_{g,t} = \rho_{bg}s^b_{g,t-1} + \sigma_{bg}\varepsilon^b_{g,t}, \tag{101}$$
$$K^p_{g,t+1} = (1-\delta_p)K^p_{g,t} + b_{g,t+1}, \tag{102}$$

where aggregate investment and its nominal price are defined by $I_t = \prod_{s=1}^{S}(\omega_{ys})^{-\omega_{ys}}(I_{s,t})^{\omega_{ys}}$ and $P^i_t = \prod_{s=1}^{S}(P^i_{s,t})^{\omega_{ys}}$, respectively. The aggregate public consumption bundle is built by a perfectly competitive public firm according to the following production technology:

$$G_t = \prod_{s=1}^{S}(\omega_{gs})^{-\omega_{gs}} G^{\omega_{gs}}_{s,t}, \tag{103}$$

where ω_{gs} is the relative weight of public consumption for goods produced in sector s ($\sum_{s=1}^{S}\omega_{gs} = 1$) or the proportion of aggregate public consumption expenditure $P^g_t G_t$ spent on sector s goods $P_{s,t}G_{s,t}$. The public firm maximises its profits (in nominal terms) by solving the following problem:

$$\max_{\{G_{s,t}\}_{s=1}^{S}} \left\{ P^g_t G_t - \sum_{s=1}^{S} P_{s,t}G_{s,t} \right\}. \tag{104}$$

The first order conditions are given by:

$$P_{s,t}G_{s,t} = P^g_t \omega_{gs} G_t, \quad s = 1, \ldots, S. \tag{105}$$

The price index of this public consumption goods aggregate will be denoted by P_t^g and obeys:

$$P_t^g = \prod_{s=1}^{S} P_{s,t}^{\omega_{gs}}. \tag{106}$$

It also satisfies $P_t^g G_t = \sum_{s=1}^{S} P_{s,t} G_{s,t}$. The government requires a fixed proportion $\bar{g} > 0$ of aggregate output as public consumption:

$$P_t^g G_t = \bar{g} \mathcal{P}_t Y_t. \tag{107}$$

Finally, the consumption and investment tax rates obey the following exogenous laws of motion:

$$\tau_{s,t}^c = (1 - \rho_\tau^c)\bar{\tau}_s^c + \rho_\tau^c \tau_{s,t-1}^c + \sigma_\tau^c \varepsilon_{\tau,s,t}^c, \quad s = 1, \ldots, S, \tag{108}$$
$$\tau_{s,t}^z = (1 - \rho_\tau^z)\bar{\tau}_s^z + \rho_\tau^z \tau_{s,t-1}^z + \sigma_\tau^z \varepsilon_{\tau,s,t}^z, \quad s = 1, \ldots, S, \tag{109}$$
$$\tau_{s,t}^i = (1 - \rho_\tau^i)\bar{\tau}_s^i + \rho_\tau^i \tau_{s,t-1}^i + \sigma_\tau^i \varepsilon_{\tau,s,t}^i, \quad s = 1, \ldots, S. \tag{110}$$

Turning to the environmental module in our economy, we have that total emissions in the economy at time t are given by:

$$\mathcal{E}_t = \sum_{s=1}^{S} \nu_s (1 - \psi_{s,t}^A) \mathring{Y}_{s,t}. \tag{111}$$

These emissions fuel the stock of carbon in the emissions via the following law of motion:

$$M_t = (1 - \delta_m) M_{t-1} + \mathcal{E}_t, \tag{112}$$

where δ_m is the fraction of carbon that leaves the atmosphere due to natural processes. Via the damage functions, the stock of carbon above pre-industrial levels M_t influences production processes negatively. To combat this externality, the fiscal authority can levy sector-specific carbon taxes that obey the following processes:

$$\tau_{s,t}^F = (1 - \rho_\tau^F)\bar{\tau}_s^F + \rho_\tau^F \tau_{s,t-1}^F + \sigma_\tau^F \varepsilon_{\tau,s,t}^F, \quad s = 1, \ldots, S. \tag{113}$$

2.9 Market clearing

In the labour market, supply meets demand when the following market clearing condition holds:

$$L_t^d = \sum_{s=1}^{S} L_{s,t}^d. \tag{114}$$

The capital stocks available in sector s are demanded by all firms in sector s. Thus, market clearing for sector s capital requires:

$$K_{s,t} = \int_{\Phi_s} K_{s,j,t}\, dj. \tag{115}$$

Market clearing in the bond and loan markets require that each bond and loan is held either by the private banking sector or the central bank which implies the following conditions:

$$B_{b,t} = B^{p}_{b,t} + B^{cb}_{b,t}, \tag{116}$$
$$B_{g,t} = B^{p}_{g,t} + B^{cb}_{g,t}, \tag{117}$$
$$L^{i}_{s,t+1} = L^{i,p}_{s,t+1} + L^{i,cb}_{s,t+1}, \quad s = 1, \ldots, S. \tag{118}$$

With the household budget constraint (7), the fiscal authority budget constraint (99), and the definitions of all the profits of all firms/producers, we can derive the following aggregate resource constraint to hold in our model:

$$\mathcal{P}_t Y_t = \sum_{s=1}^{S} P_{s,t} \mathring{Y}_{s,t} = P^{g}_t G_t + P^{c}_t C_t + \sum_{s=1}^{S} \left[P^{i}_{s,t} I_{s,t} + P_{s,t} \iota_{2s} (\psi^{A}_{s,t})^{\iota_{3s}} \mathring{Y}_{s,t} + P^{s}_t Z_{s,t} \right]. \tag{119}$$

Moreover, the following sectoral resource constraints have to hold in equilibrium:

$$\mathring{Y}_{s,t} = G_{s,t} + C_{s,t} + \iota_{2s} (\psi^{A}_{s,t})^{\iota_{3s}} \mathring{Y}_{s,t} + \sum_{r=1}^{S} I_{r,t}(s) + \sum_{r=1}^{S} Z_{r,t}(s), \quad s = 1, \ldots, S. \tag{120}$$

The model is implemented fully in real terms, using first-order perturbation methods and stochastic simulations in `dynare 4.5.4`. Appendix B contains the details on how to normalise the equations in nominal form to their real form, while the formal equilibrium definition and the steady-state equation system are relegated to Appendices C and D.

3 Calibration

This section presents an outline of the quarterly parameterisation employed in the analysis. Our model calibration is focused on the euro area, which is treated as a closed economy. The euro area encompasses 19 countries (as of 2022).[3] We obtain flow data from the FIGARO Database to calibrate the input-output matrix in the model.[4] We calibrate our model using the most recent available input-output dataset from 2021.

[3] Belgium, Germany, Estonia, Ireland, Greece, Spain, France, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Austria, Portugal, Slovenia, Slovakia, and Finland.

[4] FIGARO stands for Full International and Global Accounts for Research in Input-Output Analysis.

This database provides us with valuable insights into the trading dynamics for each combination of country and sector. Particularly, we aggregate the industries from all 19 euro area countries. This consolidation results in a unified framework of 37 sectors within what we refer to as a single country, representing the entirety of the euro area with 19 countries (EA-19). Table E.1 reports the description of the 37 sectors at the NACE-1 and NACE-2 levels we use. Since the manufacturing sector is a key sector that is particularly exposed to decarbonisation pressure, we use all the sub-sectors of the manufacturing sector (denoted by the letter C in NACE code) at NACE level 2, while all other sectors are used at the NACE level 1 only to keep the size of the model tractable.

The compiled data is used to calibrate the weights of each intermediate input in the production function of each sector, denoted by ω_{sr}. Similarly, the proportion of sectoral government expenditure, denoted by ω_{gs}, reflects the allocation of government spending across different sectors. Additionally, we calibrate consumer preferences over different types of goods, represented by ω_{cs}, which indicates the proportions of sectoral consumption within private consumption. Furthermore, the weights of sectoral production in total output, denoted by ω_{ys}, measure the relative significance of different sectors in the overall economic output. We also calibrate the sector-specific shares of intermediate inputs and labour in the value-added component of the production function using the value-added panel of the input-output table. The computation of sectoral weights for intermediate input $(1-\zeta_s)$ involves dividing the aggregate costs of intermediate inputs by total output. Simultaneously, using the value-added component for labour, we calculate the weight of labour in the value-added bundle $(1-\alpha_s)$. The residual portion of output is consequently ascribed to the sphere of capital input costs. Moreover, we can compute sector-specific carbon intensities to find the values for ν_s, which in the data and the model are expressed in megatons of carbon per trillion euro of sector-specific output.[5]

We incorporate the use of capital goods alongside standard intermediate goods in the production process. In this context, alterations impacting the suppliers of investment goods propagate through the investment matrix, ω^i_{sr}. Additionally, unlike the interactions through intermediate inputs, these effects are enduring as they influence the dynamics of capital accumulation within the economy. Although the FIGARO input-output tables cover a wide array of services as intermediate inputs, they typically lack disaggregated data on the investment (capital) inputs needed by each industry, such as machinery and buildings used in production. Instead, capital use is provided at an aggregate level in these tables through two metrics: gross fixed capital formation (GFCF) and consumption

[5]We focus exclusively on output-based emissions due to the lack of access to sectoral data on Scope 3 emissions that would be needed to compute input-based emissions. Additionally, Scope 3 emissions data is known to be of inferior quality and thus it is prudent to only use output-based emissions (Scope 1 emissions). Moreover, emissions in the literature are mostly computed in this way or based on the use of brown energy goods. Since we do not model energy goods explicitly, the latter option is not suitable in our case and we proceed with using output-based emissions.

of fixed capital (CFC). In order to calibrate the investment matrix, ω^i_{sr}, we follow Södersten et al. (2018a) and Södersten et al. (2018b). This approach leverages sector-specific capital utilisation data from the EU KLEMS database and supplements it with the symmetric 200x200-product input-output table from the EXIOBASE database.[6] We utilise the capital use matrix developed by Wood and Södersten (2022), which integrates EXIOBASE products with EU KLEMS capital types to align with the consumption of fixed capital (CFC) across industries. We match EXIOBASE products with the industries of interest and calculate the weights of each capital input within the production function of each sector. Tables E.2, E.3, and E.4 report the full set of production network parameter values for the 37-sector economy.

We categorise the considered sectors based on their greenhouse gas (GHG) emissions using the EU taxonomy, designating high-emission sectors as 'brown' and the remaining sectors as 'green'. Table E.5 displays the classification of sectors as either brown or green within our 37-sector economy at the NACE-1 and NACE-2 levels and reports the proportion of brown intermediate inputs relative to the total intermediate inputs used in the production processes.[7] The data highlights that brown sectors exhibit a notable preference for brown intermediate inputs in their production processes. Notably, the sector with the highest ratio is Electricity, Gas, Steam, and Air Conditioning Supply (D35) at 81%, closely followed by Manufacture of Basic Metals (C24), Manufacture of Paper and Paper Products (C17), and Manufacture of Food Products; Beverages and Tobacco Products (C10–C12). On the other hand, this ratio is low for green sectors such as Financial Services and Insurance Activities (K), as well as Legal and Accounting Activities; Activities of Head Offices; and Management Consultancy Activities (M). One has to be careful when interpreting these values, as they represent the direct utilisation of intermediate goods. These values could potentially differ and increase due to the indirect utilisation of brown inputs resulting from the cascading structure of the production process. As reported in Table E.2, we choose the same climate change damage function parameter across all sectors and set it to a value of $1 \cdot 10^{-8}$ so that the steady-state economic damage in all sectors is of magnitude roughly equal to 0.7%, given the stock of carbon emissions that results from all other parameter choices.

Other parameters are sourced from the literature and calibrated to mostly conventional parameters. The elasticity of substitution between inputs across sectors θ is cali-

[6] EU KLEMS is an industry level, growth, and productivity research project. EU KLEMS stands for EU level analysis of capital(K), labour (L), energy (E),materials (M), and services (S) inputs. EXIOBASE is a very detailed supply-use table, structured with a classification of 163 industries and 200 products.

[7] According to the EU Sustainable Finance Taxonomy, the sectors with the highest GHG are: Agriculture, Forestry, and Fishing (A), Mining and Quarrying (B), Manufacturing (C), Electricity, Gas, Steam, and Air Conditioning Supply (D), Water Supply, Sewerage, Waste Management, and Remediation (E), Construction (F), Transportation and Storage (H), Information and Communication (J) and Real Estate Activities (L). These sectors account for 93.2% of GHG emissions from production processes for the EU-28 in 2017.

Table 1: Model parameters

Symbol	Value	Description
f	0.5	Frisch elasticity of labour supply
χ	0.19118	Scale parameter for utility from leisure
β	0.9955	Time discount factor
ψ	0.5	Elasticity of intertemporal substitution
$\theta_{\ell s}$	6	Elasticity of substitution between differentiated labour types
$\kappa_{\ell s}$	0.75	Calvo wage setting parameter
θ	6	Elasticity of substitution between inputs across sectors
κ_s	0.75	Calvo price setting parameter in all sectors
γ_s	2	Elasticity of substitution between capital and labour in all sectors
σ_s	0.6	Elasticity of substitution between value-added and intermediate inputs in all sectors
δ_s	0.04	Depreciation rate of private capital in all sectors
ξ_s	10	Capital adjustment cost elasticity in all sectors
δ_p	0.04	Depreciation rate of public capital
$\bar{a}$	0.36022	Steady-state log total factor productivity in all sectors
$\bar{u}_s$	1	Steady-state capital utilisation rate in all sectors
ρ_u	0.8	Persistence of all sector-specific capital utilisation shocks
ρ_a	0.8	Persistence of all sector-specific technology shocks
ρ_i	0.8	Persistence of monetary policy adjustments
ρ_τ^c	0.8	Persistence of all sector-specific consumption tax rate shocks
ρ_τ^c	0.8	Persistence of all sector-specific intermediate inputs tax rate shocks
ρ_τ^i	0.8	Persistence of all sector-specific investment tax rate shocks
ρ_τ^F	0.8	Persistence of all sector-specific carbon tax rate shocks
ρ_Δ	0.8	Persistence of all sector-specific absconding rate shocks
ρ_{bg}	0.8	Persistence of public green bond issuance shock
ρ_{cb}	0.8	Persistence of all central bank QE shocks
σ_u	0	Volatility of all sector-specific capital utilisation shocks
σ_a	0.035	Volatility of all sector-specific technology shocks
σ_i	0.001	Volatility of monetary policy adjustments
σ_τ^c	0	Volatility of all sector-specific consumption tax rate shocks
σ_τ^z	0	Volatility of all sector-specific intermediate inputs tax rate shocks
σ_τ^i	0	Volatility of all sector-specific investment tax rate shocks
σ_τ^F	0	Volatility of all sector-specific carbon tax rate shocks
σ_Δ	0	Volatility of all sector-specific absconding rate shocks
σ_{bg}	0	Volatility of public green bond issuance shock
σ_{cb}	0	Volatility of all central bank QE shocks
$\bar{g}$	0.20	Public consumption to GDP ratio
ρ_{by}	0.9873	Persistence of public general bonds to GDP ratio deviations
ϕ_{by}	0.0025	Adjustment speed of public general bonds to GDP ratio to the output gap
τ^W	0.3663	Implied steady-state labour income tax rate
θ_b	0.974	Bank survival probability
φ	0.006	Size of bank start-up fund
χ_s	22.5	Fraction of investment expenditure financed by loans in all sectors
Δ_{bb}	$2/3 \cdot 0.55$	Absconding rate adjustment factor for public general bonds
Δ_{bg}	$0.5 \cdot 0.55$	Absconding rate adjustment factor for public green bonds
$\bar{\Pi}$	1	Steady-state gross inflation
ϕ_π	1.50	Weight of inflation gap in the Taylor rule
ϕ_y	0.25	Weight of output gap in the Taylor rule
δ_m	0.0021	Carbon decay parameter
ι_{2s}	4	Abatement investment parameter 1 in all sectors
ι_{3s}	2.6	Abatement investment parameter 2 in all sectors
$\bar{\tau}_s^c$	0.25	Steady-state consumption tax rate in all sectors
$\bar{\tau}_s^z$	0.25	Steady-state intermediate inputs tax rate in all sectors
$\bar{\tau}_s^F$	2e-5	Steady-state carbon tax rate in all sectors
$\bar{\tau}_s^i$	0	Steady-state investment tax rate in all sectors
$\bar{\Delta}_s$	0.55	Steady-state absconding rate in all sectors
$\bar{s}_b^{cb}$	0	Steady-state public general bonds holdings of the monetary authority
$\bar{s}_g^{cb}$	0	Steady-state public green bonds holdings of the monetary authority
$\bar{s}_{\ell,s}^{cb}$	0	Steady-state corporate loan holdings of the monetary authority in all sectors

Notes: This table reports both conventional values from the literature and data-implied values for the parameters of our benchmark calibration of the model, described in Section 2. Values for the sector specific parameters are provided in Tables E.2, E.3, and E.4.

brated to be 6 which implies a monopoly markup μ of 20% for intermediate goods firms. The Calvo price setting probability is set to 25%, which implies $\kappa_s = 0.75$, or an average price-setting frequency of four quarters in all sectors.[8] For simplicity, the labour unions' mark-ups and wage-setting frequencies are set to the same values, i.e. $\theta_{\ell s} = 6$ and $\kappa_{\ell s} = 0.75$. The Taylor rule weights for inflation and output gap are chosen to be $\phi_\pi = 1.5$ and $\phi_y = 0.25$, while the persistence of monetary policy adjustments is equal to $\rho_i = 0.8$. The persistence parameters of all other shocks are set for simplicity to the same value, i.e. $\rho_u = \rho_a = \rho_\tau^c = \rho_\tau^z = \rho_\tau^i = \rho_\tau^F = \rho_\Delta = \rho_{bg} = \rho_{cb} = 0.8$. Moreover, there is no steady-state inflation in the model, i.e. steady-state gross quarterly inflation is $\bar{\Pi} = 1$. All these parameters are used widely in the literature, see for a recent example Sims and Wu (2021). The time discount factor is slightly higher than in Sims and Wu (2021) and chosen to be $\beta = 0.9955$, implying an annual log nominal interest rate of roughly 1.8 percentage points. The Frisch elasticity of labour supply f is chosen to be 0.5, in line with well-known models of the euro area such as the New-Area-Wide model (Coenen et al., 2007; Christoffel et al., 2008; Coenen et al., 2023) or the EAGLE model (Gomes et al., 2010; Bokan et al., 2018). The scale parameter for utility from leisure time is chosen to induce a steady-state labour demand by firms of 1, while the elasticity of intertemporal substitution is set to the conventional value of $\psi = 0.5$.

The capital depreciation rates in all sectors are set to a quarterly value of 0.04 to produce a reasonable aggregate investment to GDP ratio, relative to the empirical euro area counterpart for the period 1999–2023. For simplicity, the public green capital depreciation rate δ_p is set to the same value. The capital adjustment cost elasticities are set to $\xi_s = 10$ to feature a relatively swift response of investment to capital utilisation shocks or other economic shocks in order to produce substantial investment growth volatility. The elasticities of substitution between value-added and intermediate inputs and between capital are set to $\gamma_s = 2$ and $\sigma_s = 0.6$, so that it is assumed that it is easier to substitute between capital and labour than it is between value-added and intermediate inputs. The steady-state log total factor productivity in all sectors $\bar{a}$ is implied by requiring that aggregate output Y_t is equal to 18.42/4, which is euro area GDP in trillion euro in 2019, computed by taking the sum of output values of all sectors using our sector-specific data, divided by 4 since the model features quarterly frequency. This is needed to ensure that the carbon tax rates can be measured in a meaningful way (i.e. trillion euro per megatons of carbon) and that the emission intensities ν_s correspond to the data counterparts.

In the banking sector, the bank survival probability is equal to 0.974, as in Carattini et al. (2024) and close to the value chosen by Gertler and Karadi (2013). The size of the bank start-up fund is chosen so that the model reproduces the bank leverage ratio

[8] For our results, using different price-setting frequencies for different sectors does not seem to matter much quantitatively. Using unreported results, we establish this finding. In these additional unreported simulations, we set the price-setting frequencies to the ones chosen by Hinterlang et al. (2022), where we average their price-setting frequencies at the NACE 2 level for which we only use the corresponding NACE 1 level sector in our economy. These additional results are not reported to conserve space but available upon request from the authors.

in euro area data, while the fraction of investment expenditures financed by loans in all sectors is set to $\chi_s = 22.5$ in order to match the aggregate loan to annualised GDP ratio in the data. In order to let the model reproduce the average corporate loan interest rates in euro area data, the steady-state absconding rates in all sectors are set to $\bar{\Delta}_s = 0.55$.

The abatement investment parameters are set to $\iota_{2s} = 4$ and $\iota_{3s} = 2.6$, where the second parameter choice follows Benmir and Roman (2022). The steady-state carbon tax rate is set to 20 euro per ton of carbon, which implies setting $\bar{\tau}_s^F = 2\text{e-}5$ as the carbon tax rates are measured in trillion euro per megatons of carbon. The consumption and intermediate inputs tax rates are set to 25% and the investment tax rates to 0 which implies a steady-state labour income tax rate of 36.63%. Also in line with the data and a conventionally used value is the calibrated public consumption to GDP ratio of 20%, i.e. $\bar{g} = 0.2$. The fiscal rule features a large persistence of $\rho_{by} = 0.9873$ and a moderate adjustment speed of public general bonds to GDP to the output gap of $\phi_{by} = 0.0025$. The absconding rates of public general bonds and public green bonds are set to two thirds and one half of the value for corporate loans, respectively.

Finally, we assume that the monetary authority holds 10% of all corporate loans outstanding in all sectors.

Table 1 reports all the aggregate parameter values and sectoral parameters set to the same value in all sectors along with their corresponding descriptions.

Before using the model for policy analysis, we simulate the model and compute several moments to compare them to their empirical counterparts from euro area data for the period 1999–2023. Table 2 reports the results. The model almost reaches the empirical counterpart for the aggregate investment to GDP ratio, where aggregate investment in the model is defined by $I_t = \prod_{s=1}^{S}(\omega_{ys})^{-\omega_{ys}}(I_{s,t})^{\omega_{ys}}$, similar to aggregating sectoral outputs to aggregate GDP, and the aggregate (nominal) investment price by $P_t^i = \prod_{s=1}^{S}(P_{s,t}^i)^{\omega_{ys}}$. Similarly, we define $Z_t = \prod_{s=1}^{S}(\omega_{ys})^{-\omega_{ys}}(Z_{s,t})^{\omega_{ys}}$, $P_t^z = \prod_{s=1}^{S}(P_t^s)^{\omega_{ys}}$, $G_t = \prod_{s=1}^{S}(\omega_{gs})^{-\omega_{gs}}(G_{s,t})^{\omega_{gs}}$, and $P_t^g = \prod_{s=1}^{S}(P_t^s)^{\omega_{gs}}$, where the corresponding ratios to GDP are reasonably well reproduced by the model. The average nominal loan interest rates across sectors are also well matched, while the model's nominal risk-free rate and deposit interest rate are higher than in the data. The aggregate loan to annualised GDP ratio is very well reproduced by the model, as is the bank leverage ratio. Turning to second moments, the model does well in reproducing GDP growth rate volatility, real loan interest rate volatility, and real deposit interest rate volatility, but produces too little aggregate consumption growth rate volatility and aggregate investment growth rate volatility.

Table 2: Simulated model moments and data counterparts

Moment	Description	Model	Data
$\mathbb{E}[i_t]$	Log nominal risk-free rate	1.80	0.92
$\mathbb{E}[R^i_{g,t}]$	Log nominal green corporate loan interest rate	3.19	3.34
$\mathbb{E}[R^i_{b,t}]$	Log nominal brown corporate loan interest rate	3.19	3.34
$\mathbb{E}[R^d_t]$	Log nominal deposit interest rate	1.80	0.45
$\mathbb{E}\left[\frac{p^i_t I_t}{Y_t}\right]$	Aggregate investment to GDP ratio	17.45	21.10
$\mathbb{E}\left[\frac{p^g_t G_t}{Y_t}\right]$	Aggregate public consumption to GDP ratio	20.00	20.58
$\mathbb{E}\left[\frac{p^z_t Z_t + p^c_t C_t}{Y_t}\right]$	Aggregate intermediate input and consumption to GDP ratio	69.71	54.79
$\mathbb{E}\left[\frac{\ell_t}{4Y_t}\right]$	Aggregate loan to annualised GDP ratio	103.43	104.30
$\mathbb{E}\left[\frac{\ell^p_t}{\mathrm{nw}_t}\right]$	Bank leverage ratio	4.59	4.57
$\sigma(\Delta y_t)$	Log GDP growth rate volatility	2.12	2.05
$\sigma(\Delta c_t)$	Log aggregate consumption growth rate volatility	1.40	2.30
$\sigma(\Delta i_t)$	Log aggregate investment growth rate volatility	2.58	4.36
$\sigma(r^i_{g,t})$	Log real green corporate loan interest rate volatility	1.85	2.29
$\sigma(r^i_{b,t})$	Log real brown corporate loan interest rate volatility	1.85	2.29
$\sigma(r^d_t)$	Log real deposit interest rate volatility	1.90	2.02

Notes: This table reports the simulated model moments and the corresponding euro area data counterparts for the period 1999–2023 (see Appendix F for the data details) for a variety of macroeconomic variables. The model moments have been obtained from a stochastic simulation of the model for 100000 periods (quarters) using a first-order perturbation approximation in `dynare` (version 4.5.4). All moments are annualised and reported in percentage points.

4 Analysis

In this section, we study the equilibrium effects of various shocks that are expected to either affect a brown aspect of the economy negatively or a green aspect positively.

The results are presented by means of constructing impulse response functions to a one-time shock in period 1 in one or several exogenous processes. The shocks are persistent with persistence parameter 0.8 and will thus affect the economy beyond the initial effect for several periods significantly. We depict 40 periods where the model is initially (period 0) in the steady state, the shocks occur in period 1, and then no further shock is fed into the model afterwards. For the definition of the variables in the impulse response functions, we define the followings subsets of sectors: $\mathcal{S}_g$ ($\mathcal{S}_b$) is the subset of green (brown) sectors in our 37-sector economy, as specified in Table E.2. The variables depicted in each set of graphs are: (A) aggregate final goods output (GDP) Y_t; (B) aggregate consumption C_t; (C) aggregate inflation Π_t; (D) aggregate carbon emissions $\mathcal{E}_t$; (E) bank leverage ratio $\mathrm{LEV}_t = (\mathrm{nw}_t)^{-1}\left(b^p_{b,t+1} + b^p_{g,t+1} + \sum_{s=1}^{S} \ell^{i,p}_{s,t+1}\right)$ as a measure for inverse financial stability; (F) real average wage w_t; (G) the nominal interest rate i_t; (H) the real interest rate r_t; (I) final goods output of the brown sectors $Y_{b,t} = \sum_{s\in\mathcal{S}_b} P_{s,t}\mathring{Y}_{s,t}$; (J) final goods output of the green sectors $Y_{g,t} = \sum_{s\in\mathcal{S}_g} P_{s,t}\mathring{Y}_{s,t}$;

(K) consumption of the brown sectors' goods $C_{b,t} = \sum_{s\in\mathcal{S}_b} P_{s,t}C_{s,t}$; (L) consumption of the green sectors' goods $C_{g,t} = \sum_{s\in\mathcal{S}_g} P_{s,t}C_{s,t}$; (M) labour demand by the brown sectors $L^d_{b,t} = \sum_{s\in\mathcal{S}_b} L_{s,t}$; (N) labour demand by the green sectors $L^d_{g,t} = \sum_{s\in\mathcal{S}_g} L_{s,t}$; (O) capital investment by the brown sectors $I_{b,t} = \sum_{s\in\mathcal{S}_b} P^i_{s,t}I_{s,t}$; (P) capital investment by the green sectors $I_{g,t} = \sum_{s\in\mathcal{S}_g} P^i_{s,t}I_{s,t}$; (Q) real brown sectors' loan stock $\ell_{b,t} = \sum_{s\in\mathcal{S}_b} \ell_{s,t}$; (R) real green sectors' loan stock $\ell_{g,t} = \sum_{s\in\mathcal{S}_g} \ell_{s,t}$; (S) average nominal corporate loan interest rate in the brown sectors $R^i_{b,t} = 1/Y_{b,t} \cdot \sum_{s\in\mathcal{S}_b} P_{s,t}\mathring{Y}_{s,t}R^i_{s,t}$; and (T) average nominal corporate loan interest rate in the green sectors $R^i_{g,t} = 1/Y_{g,t} \cdot \sum_{s\in\mathcal{S}_g} P_{s,t}\mathring{Y}_{s,t}R^i_{s,t}$.

We discuss scenarios related to financial regulation and fiscal policy in the following sections, while some additional scenarios are reported in Appendix G that are not the focus of this paper; however, these scenarios have been studied in our previous paper that does not feature a banking sector (Grüning and Kantur, 2023). In particular, the effects of shocks to capital utilisation rates and the increase in the consumption tax in brown sectors are reported in Appendix G.

4.1 Financial regulation scenarios

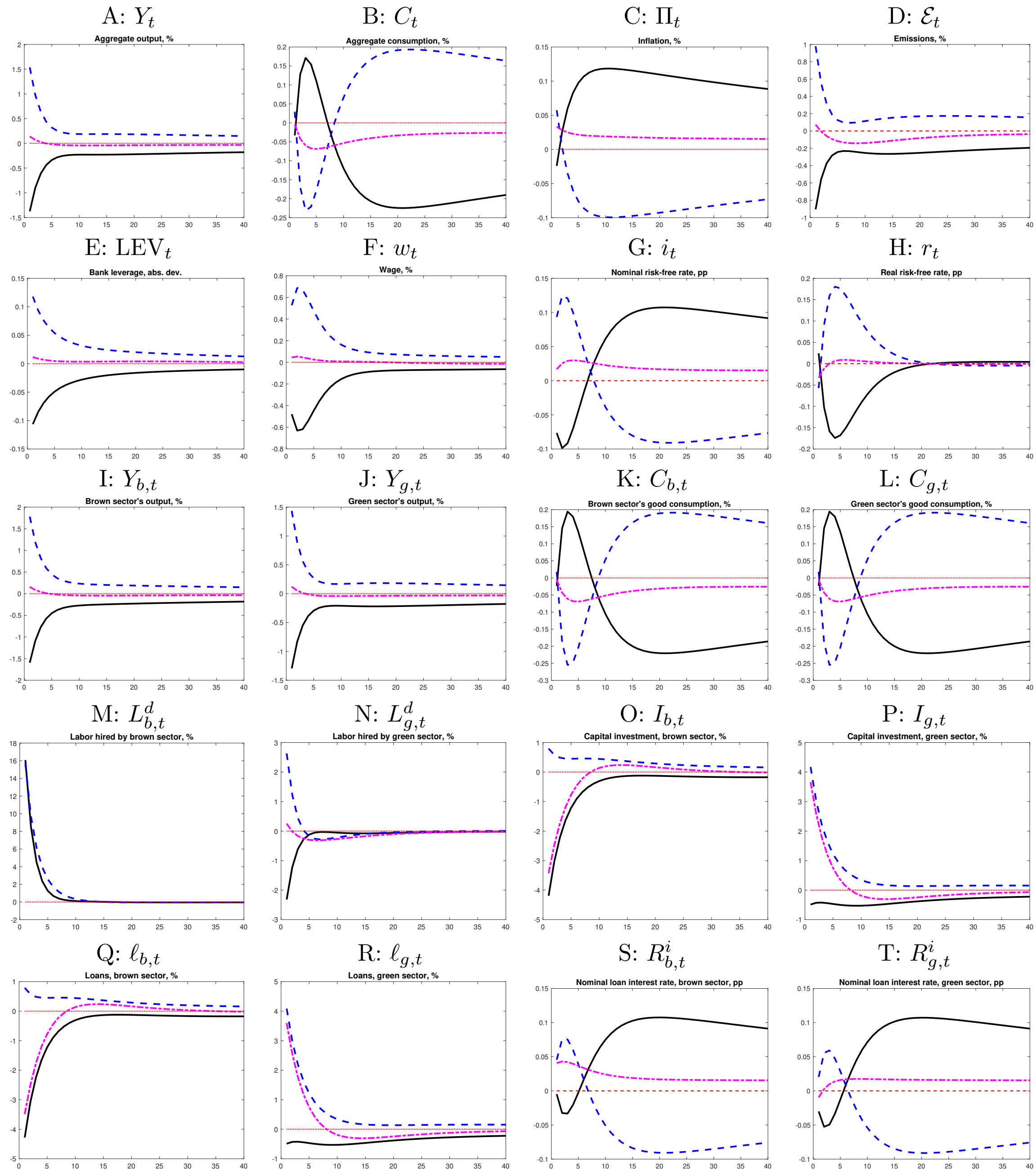
Financial regulation plays a critical role in addressing climate change by influencing the allocation of capital between green and brown sectors. In this part, we consider two distinct scenarios as financial regulation. Changes in the absconding rate for brown and green loans can significantly impact the cost of borrowing and investment decisions. For instance, an increase in the absconding rate for brown sector loans raises their risk weight, making them more expensive and thereby discouraging investment in carbon-intensive projects. Conversely, reducing the absconding rate for green sector loans makes green investments cheaper and more attractive. Additionally, we examine the impact of regulatory measures such as Green Quantitative Easing (QE) and Brown Quantitative Tightening (QT). These unconventional monetary policy tools can further shape financial flows. Green QE involves central banks purchasing green assets to stimulate investment in sustainable projects, while Brown QT entails reducing exposure to carbon-intensive assets to curb investment in high-emission activities. Together, these regulatory strategies help steer financial resources toward low-carbon investments, fostering a transition to a more sustainable economy while mitigating the adverse effects of climate change.

Absconding rate shocks. As households become more concerned about climate change, they adjust their portfolios toward funds with better climate ratings, such as mutual fund holdings within the Swedish pension system (Anderson and Robinson, 2019). This shift in investment behaviour of depositors significantly impacts the banking sectors' loan supply preferences. Banks can effectively allocate credit facilities for green energy projects while limiting loans to capital carbon-intensive projects. By making brown assets more expensive, financial flows can be more easily redirected toward projects that support the transition to a low-carbon economy. In this section, we examine three different scenarios regarding absconding rate changes, which affect the relative cost of green and brown investments by improving or deteriorating the quality of the green or brown loan portfolio, respectively. In the first scenario, we simulate a situation where there is a 4 percentage points (pps) increase in the absconding rates of the brown sector, leading to an increase in the risk associated with brown sector investments. Hence, the loans in brown sectors become more expensive compared to green loans for banks to issue. In the subsequent scenario, we explore a similar case where there is a 4 pps decline in the absconding rate, making green loans cheaper. Finally, we analyse a combination of the aforementioned scenarios. The choice of 4 percentage points is motivated by the fact that a change of this size in the deterministic state implies a change of the nominal quarterly loan interest rates charged by the banks to firms of 2.5 basis points or, in annual terms, 10 basis points. This size is consistent with empirical evidence, summarised by Dagher et al. (2016), that a change of 1 percentage point in the bank capital requirement implies a change of 1–20 basis points in annual loan interest rates, implying that the mid-point of these estimates is 10 basis points.

Figure 2 depicts all the impulse response functions for these three scenarios. The black solid lines depict the exogenous increase in the absconding rate of the brown sector, while the blue dashed lines represent the decline in the absconding rate of the green sector. The magenta dash-dotted lines illustrate the combination of these two scenarios.

In the first case, a 4 pps increase in the absconding rate leads to a higher risk-weight assigned to brown sector loans, thereby discouraging investments in carbon-intensive sectors. Hence, loans, investment, and output in the brown sector decline (Panels Q, O, and I). Due to the interconnected nature of intermediate input and investment networks, this downturn in the brown sectors also impacts the green sectors, leading to a reduction in green output (Panel J) and, subsequently, in aggregate output (Panel A). In the short run, this scenario leads to a decrease in inflation (Panel C). However, as monetary policy responds with expansionary measures (Panel G), inflation rises in the medium term. The initial increase in real interest rates causes a decline in both sector-specific and aggregate consumption in the short run (Panels K, L, and B). While consumption rebounds following the monetary policy adjustments, a negative income effect results in a subsequent decline in the medium run. Emissions decrease due to the overall decline in output (Panel D). However, there is no significant transition to a greener economy in terms of production, given the investment and intermediate input linkages among sectors. For financial stability, we see an improvement (Panel E), since bank leverage decreases by 0.1 from a steady-state level of around 4.6. This might not sound much but roughly equals the quarterly standard deviation of the empirical counterpart for the period 2015–2023

Figure 2: Impulse response functions – absconding rate shocks



Notes: This figure depicts impulse response functions for exogenous changes in absconding rates. The black solid lines correspond to the simulation that sees an exogenous increase of 4 percentage points in the absconding rates of the brown sectors, while the blue dashed lines depict the economic effects of an exogenous decrease of 4 percentage points in the absconding rates of the green sectors in period 1. Finally, the magenta dash-dotted lines correspond to a combination of the two aforementioned simulations. A 4 percentage points change in the absconding rate is equivalent to a 2.5 basis points change (i.e. 10 basis points annually) in the loan interest rate in the steady state.

(the exact value of this standard deviation is 0.12).[9] Hence, the reduction in our model

[9] Since the bank leverage ratios in the euro area have decreased significantly after the Global Financial Crisis, we compute the standard deviation only from the first quarter of 2015 onward as since then the leverage ratio has fluctuated around 4, while the average level was around 5 for the period 1999–2014.

equals a one standard deviation shock, which is an economically significant improvement in financial stability.

In the second case, we examine the opposite situation in which the risk-weight assigned to the green sector loans falls. As a result, the cost of green loans becomes lower, leading to an increase in demand for green loans. The resulting boost in green investment (Panel P) drives up green output (Panel J). Since green production relies on brown intermediate inputs and investment goods, the increased demand for green output subsequently raises the demand for brown output (Panel I), leading to a modest rise in brown loans and investment (Panels Q and O). The overall increase in output from both sectors contributes to a rise in aggregate output (Panel A). In the medium run, inflation falls due to a monetary policy tightening (Panels C and G). In the short run, both sector-specific and aggregate consumption levels decline as a result of tighter monetary policy (Panels K, L, and B) . However, as the real average wage rises, the income effect ultimately leads to an increase in consumption levels. Although this scenario leads to a greater increase in green investments compared to brown investments, the high dependence of green production on brown inputs drives up the demand for brown goods and, consequently, output. As a result, we observe an increase in emissions, indicating that, from an environmental perspective, the overall impact remains unfavourable (Panel D). In addition, financial stability considerably worsens since banks see an increase in their leverage ratio by about 0.12 initially.

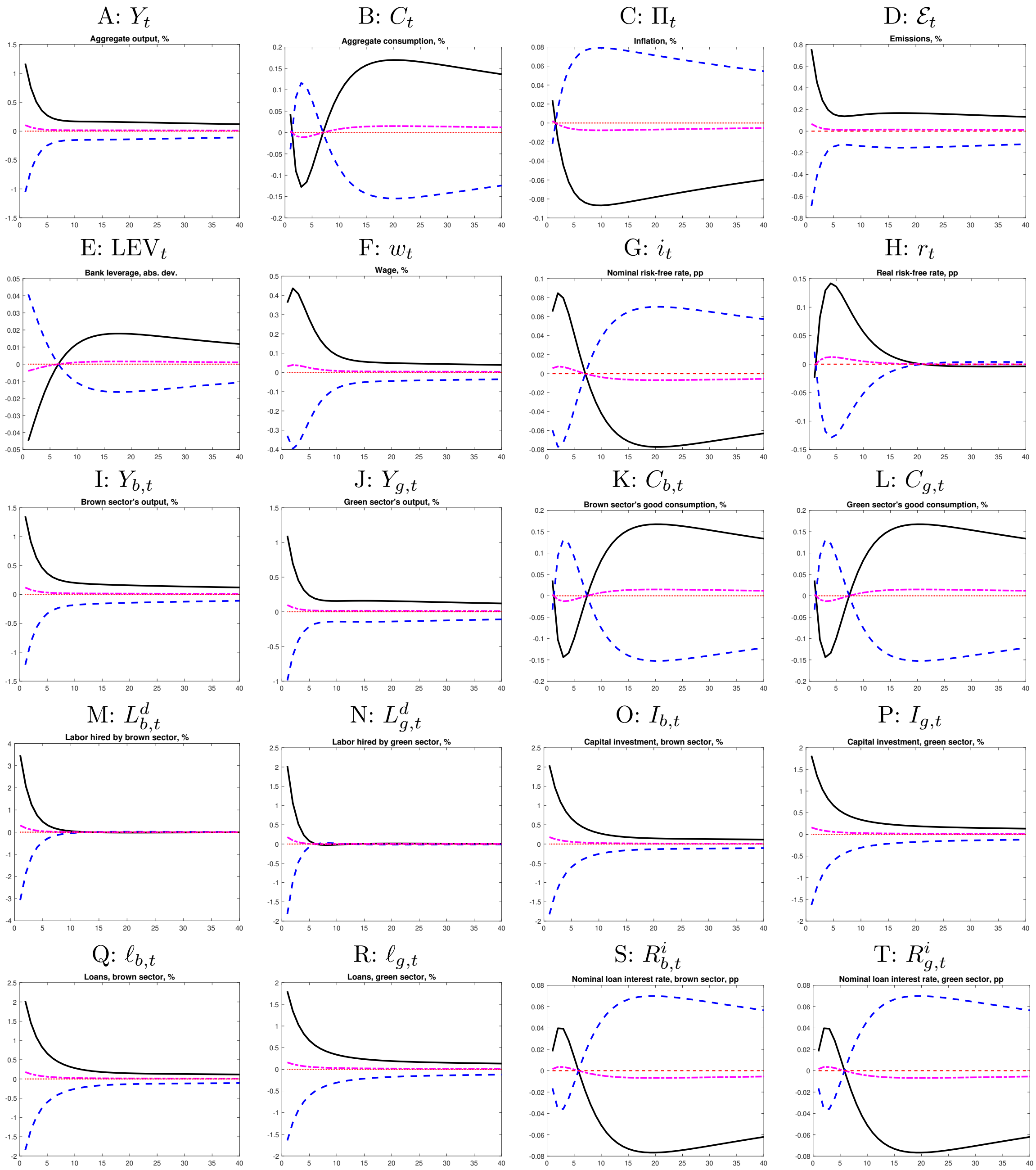
In our final case, we examine scenarios where brown investments become more expensive while green investments become cheaper. This dynamic leads to an increase in green loans and a decrease in brown loans, fostering a transition from brown to green investments (Panels O and P). Consequently, capital allocation shifts from brown to green sectors. However, the impact on sector-specific and aggregate output levels remains limited due to the insufficient increase in brown intermediate inputs used by the green sector. As a result, the shift in output is not substantial, with only a modest rise in aggregate output. In response, monetary policy adjusts by raising interest rates slightly (Panel G), leading to lower aggregate consumption (Panel B). Despite these adjustments, emissions remain unchanged because the overall output levels are not significantly impacted by the changes in the absconding rate (Panel D) and also bank leverage hardly reacts (Panel E).

QE and QT policies. In this analysis, we focus on the role of central banks in the decarbonisation process and consequences of central banks actions for macro-financial stability. We investigate whether central banks can effectively contribute to the transition to a low-carbon economy through Green QE (or Brown QT). This approach involves shifting monetary authorities' holdings of privately-issued financial assets towards the green sectors of the economy. In this context, we conduct three experiments with unconventional monetary policy tools, as illustrated in Figure 3. In the first scenario, represented by the black solid lines, the central bank initiates a Green QE programme by purchasing an additional 5% of the outstanding corporate bonds in the green sectors. The second scenario, illustrated with blue dashed lines, depicts the impact of Brown QT, where the central bank reduces its brown sector corporate bonds holdings by 5% of the total outstanding amounts in the economy. Finally, the effects of combining both scenarios are depicted using magenta dash-dotted lines. This scenario is akin to a portfolio rebalancing of the central bank, i.e. a shift from brown to green assets.

In the first scenario, the monetary authority purchases green corporate bonds, exerting downward pressure on green bond yields and thereby reducing the green loan costs for banks. This leads to a significant increase in loans to the green sectors (Panel R), followed by a rise in investment expenditures (Panel P) and green output (Panel J). Due to the interconnected nature of capital and intermediate inputs in the production of final and investment goods, we also observe an increased demand for brown investment goods (Panel O) and output (Panel I), accompanied by a simultaneous rise in loans in the brown sector (Panel Q). Consequently, aggregate output increases due to the expansionary nature of the QE policy, which in turn leads to higher emissions (Panel D). We observe an immediate fall in the real risk-free rate, followed by a rise in the medium run (Panel H). As a direct response to the initial drop in real interest rates, sector-specific consumption levels rise but subsequently decline as real interest rates adjust. However, the positive income effect causes sector-specific and aggregate consumption levels to increase once again in the medium run. The effect on bank leverage is mixed with a decline in the short run of maximum 0.05 (or half an empirical standard deviation) and a small increase in the medium to long run (Panel E).

In the second scenario, we examine the case where the central bank sells 5% of the outstanding corporate bonds issued by brown sectors from its balance sheet. The responses to this shock are symmetric to those observed in the first scenario. As the central bank offloads brown corporate bonds, there is upward pressure on brown bond yields, increasing the brown loan costs. Consequently, loans to the brown sectors decrease significantly, leading to a reduction in brown investment expenditures and brown output (Panels O and I). This contraction in brown sector activity causes a decline in the demand for green investment goods and output, resulting in a simultaneous decrease in green loans, green investment, and green output. Aggregate output falls due to the contractionary nature of the QT policy, leading to a decrease in emissions. Inflation falls initially in response to the contractionary policy but increases in the medium run following the adjustment of interest rates. The nominal risk-free rate rises initially but falls in the medium run. Sector-specific and aggregate consumption levels decline immediately due to the increase in the real risk-free rate, but they rise again in the medium run due to the positive income effect, leading to an overall increase in sector-specific and aggregate consumption. Due to the economic contraction, the consumption levels finally decrease in the longer run.

Figure 3: Impulse response functions – QE/QT shocks



Notes: This figure depicts impulse response functions for QE and QT shocks by the monetary authority in period 1. For the black solid lines, the central bank buys an additional 5% of the outstanding corporate bonds in the green sectors to implement a Green QE programme. For the blue dashed lines, the central bank sells 5% of the outstanding corporate bonds in the brown sectors that are on its balance sheet, i.e. a brown QT shock. The magenta dash-dotted lines combine the aforementioned Green QE and the Brown QT shocks.

As a final case, we combine the aforementioned policies to reinforce the impact of transitioning to a greener economy. Specifically, the central bank implements both Green QE and Brown QT simultaneously. The intention is to amplify the shift from brown to green investments by both promoting green bond purchases and reducing brown bond holdings. However, due to the strong interlinkages between the sectors, the effects of QE and QT are found to be symmetric and the responses counterbalance each other. This results in a net neutral impact on the overall economy, as the expansionary effects of Green QE are offset by the contractionary effects of brown QT. It is worth mentioning that the timing and context of these policies also play a critical role. QE is typically implemented and more effective during periods when the zero lower bound constrains conventional monetary policy, aiming to stimulate the economy by lowering long-term interest rates and encouraging investment. In contrast, QT is generally executed when the monetary policy rate is already positive, intending to tighten monetary conditions by raising long-term interest rates and curbing investment. The simultaneous implementation of these policies in our analysis highlights the complex interactions within the economy and underscores the importance of considering sectoral interdependencies and the broader economic context when designing and deploying such policies. As a final remark, while the combined approach theoretically aims to accelerate the transition to a greener economy, the practical outcome is less effective due to the canceling effects of the policies. This highlights the need for an understanding of the economic environment and the timing of policy implementation to achieve the desired objectives in promoting sustainable growth. As with combined absconding rate shocks, in the combined QE/QT scenario bank leverage or financial stability is not significantly affected.

It is worth mentioning at this point that we find rather large economic effects of bank regulation shocks, i.e. absconding rate shocks in our model, and QE/QT shocks relative to several notable contributions in the literature (Benmir and Roman, 2022; Abiry et al., 2022; Ferrari and Nispi Landi, 2024; Giovanardi and Kaldorf, 2024). To be sure that this is not due to the large amount of loans the firms have to take (i.e. 22.5 times their investment expenditure), we have simulated the aforementioned absconding rate and QE/QT scenarios also when $\chi_s = 1$ for all $s = 1, \ldots, S$, i.e. when firms only have to take loans in the exact amount of their investment expenditures. The effects become smaller but only by a relatively small margin.[10] Thus, the large effects we find are probably due to the multi-sector framework we employ as the aforementioned studies employ one- or two-sector models to study the effects of non-standard climate change policies like bank regulation and monetary policies.

4.2 Fiscal policy scenarios

In the previous section, we have explored the impact of financial regulation scenarios on both macro-financial stability and environmental dynamics. In this section, we shift our focus to fiscal policy scenarios, examining three distinct cases. First, we analyse the effect of an increase in the carbon tax on the economy, considering various forms of revenue recycling such as transfers to households, investment subsidies to the green

[10]To conserve space, these results are not shown but available from the authors upon request.

sectors, and investments in building public green capital. Next, we compare the responses to a standard positive technology shock in green sectors with those observed when the government boosts the productivity of the green sector by building green public capital, financed through the issuance of green public bonds. Finally, we explore the impact of investment tax shocks in the brown sectors and investment subsidy shocks in the green sectors.

Carbon tax and revenue recycling. First, we analyse the impacts of increasing carbon taxes, a direct approach to addressing environmental concerns and a crucial element of sustainable development. Figure 4 illustrates the impulse response functions for an exogenous increase in the carbon tax by 20 euro per ton of carbon, effectively doubling the tax from 20 to 40 euro for all sectors starting in period 1. In our analysis, we consider various forms of revenue recycling in conjunction with the carbon tax policy, including lump-sum transfers to households (black solid lines), investment subsidies to the green sectors (blue dashed lines), and investments in public green capital (magenta dash-dotted lines).[11]

Since the carbon tax increase leads to larger costs in all sectors and in particular for sectors with high emission intensities (the brown sectors), output declines are observed in both green and brown sectors. Due to the green sectors requiring inputs also from the brown sectors, the decline in the green sectors is not significantly smaller than in the brown sectors. Inflation rises due to the tax shock, which in turn leads to an increase in nominal interest rates. As a result, consumption levels fall significantly. Consequently,

[11]For carbon tax recycling in the form of investment subsidies to the green sectors, remove T_t from the household budget constraint (7). Additionally, the exogenous processes for the capital investment taxes in the green sectors (Equation 110 for those sectors s that are classified as green in Table E.2) are removed from the system of equations and replaced by the following endogenous termination of the capital investment tax rates in the green sectors:

$$\sum_{s\in\mathcal{S}_g}[\tau^i_{s,t}P^i_{s,t}I_{s,t}] = -T_t,$$
$$\tau^i_{j,t} = \tau^i_{k,t}, \quad \forall\ j \neq k \in \mathcal{S}_g,$$

where $\mathcal{S}_g$ ($\mathcal{S}_b$) are the subsets of green (brown) sectors in our 37-sector economy. Finally, the government budget constraint (99) is replaced by the following version (T_t added to the right hand side):

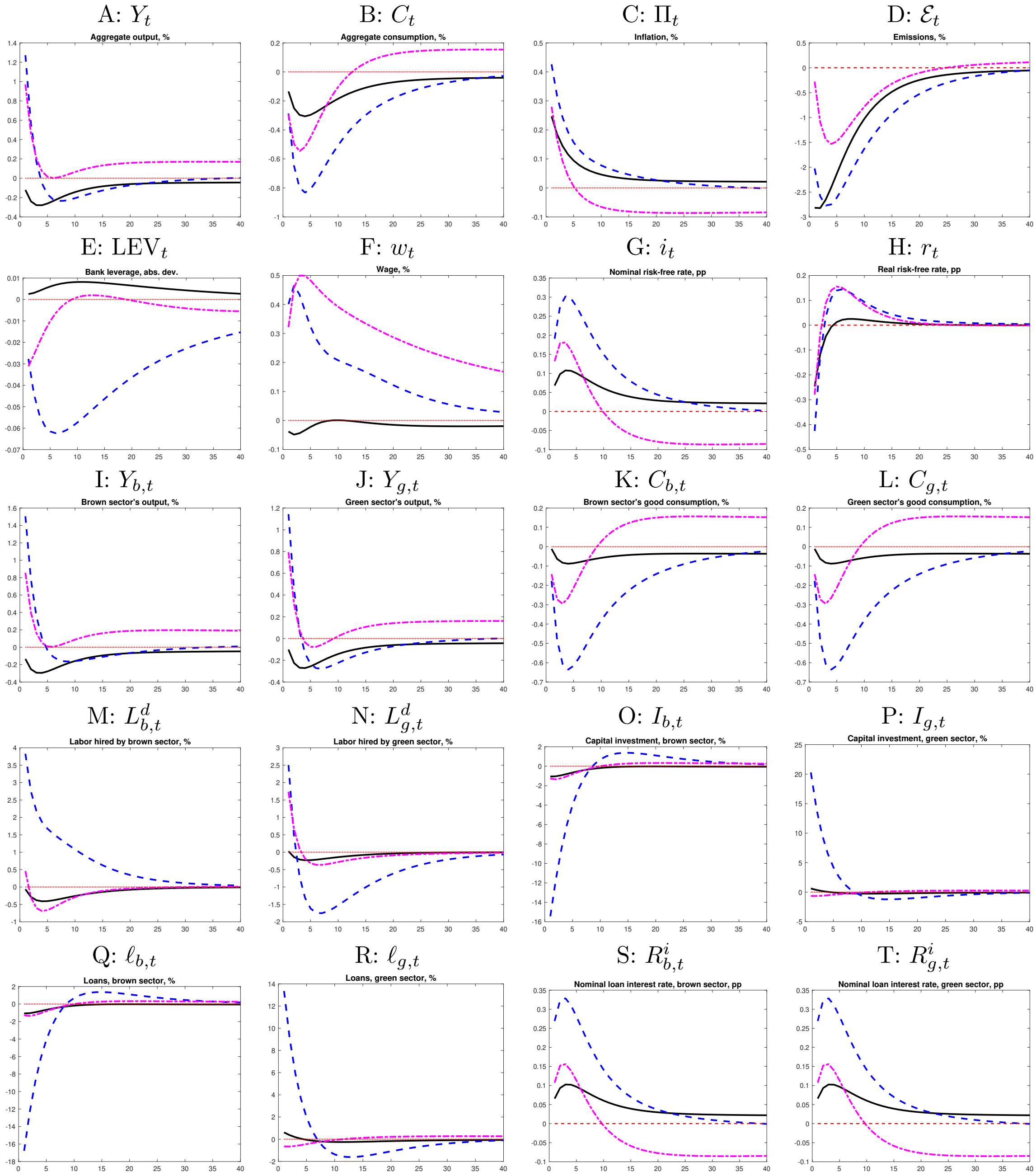
$$R^b_{b,t-1}B_{b,t}+R^b_{g,t-1}B_{g,t}+\sum_{s=1}^{S}G_{s,t} = T_{cb,t}+T_t+B_{b,t+1}+B_{g,t+1}+\tau^W_t\sum_{s=0}^{S}W_{s,t}L^d_{s,t}+\sum_{s=1}^{S}\left[\tau^c_{s,t}P_{s,t}C_{s,t}+\tau^i_{s,t}P^i_{s,t}I_{s,t}+\tau^z_{s,t}P^s_tZ_{s,t}\right].$$

For carbon tax recycling in the form of investments in public green capital, the model is modified as follows. Remove T_t from the household budget constraint (7), add the carbon tax revenue in sector s, i.e. $\tau^F_{s,t}\nu_s(1-\psi^A_{s,t})\mathring{Y}_{s,t}$, to the right-hand side of the sectoral resource constraint (120), and replace the equation for public green capital accumulation (102) by the following one:

$$K^p_{g,t+1} = (1-\delta_p)K^p_{g,t} + b_{g,t+1} + T_t.$$

we observe a decline in emissions due to the overall reduction in production prompted by the carbon tax increase and the increase in abatement efforts.

Figure 4: Impulse response functions – carbon tax shock and type of revenue recycling



Notes: This figure depicts impulse response functions for an exogenous increase in the carbon tax equal to 20 euro per ton of carbon (i.e. a doubling of the carbon tax from 20 to 40 euro) in all sectors in period 1. The black solid lines correspond to carbon tax revenue recycling in the form of a lump-sum transfer to households, the blue dashed lines to carbon tax revenue recycling in the form of investment subsidies to the firms in the green sectors, and the magenta dash-dotted lines to carbon tax revenue recycling in the form of investment in public green capital.

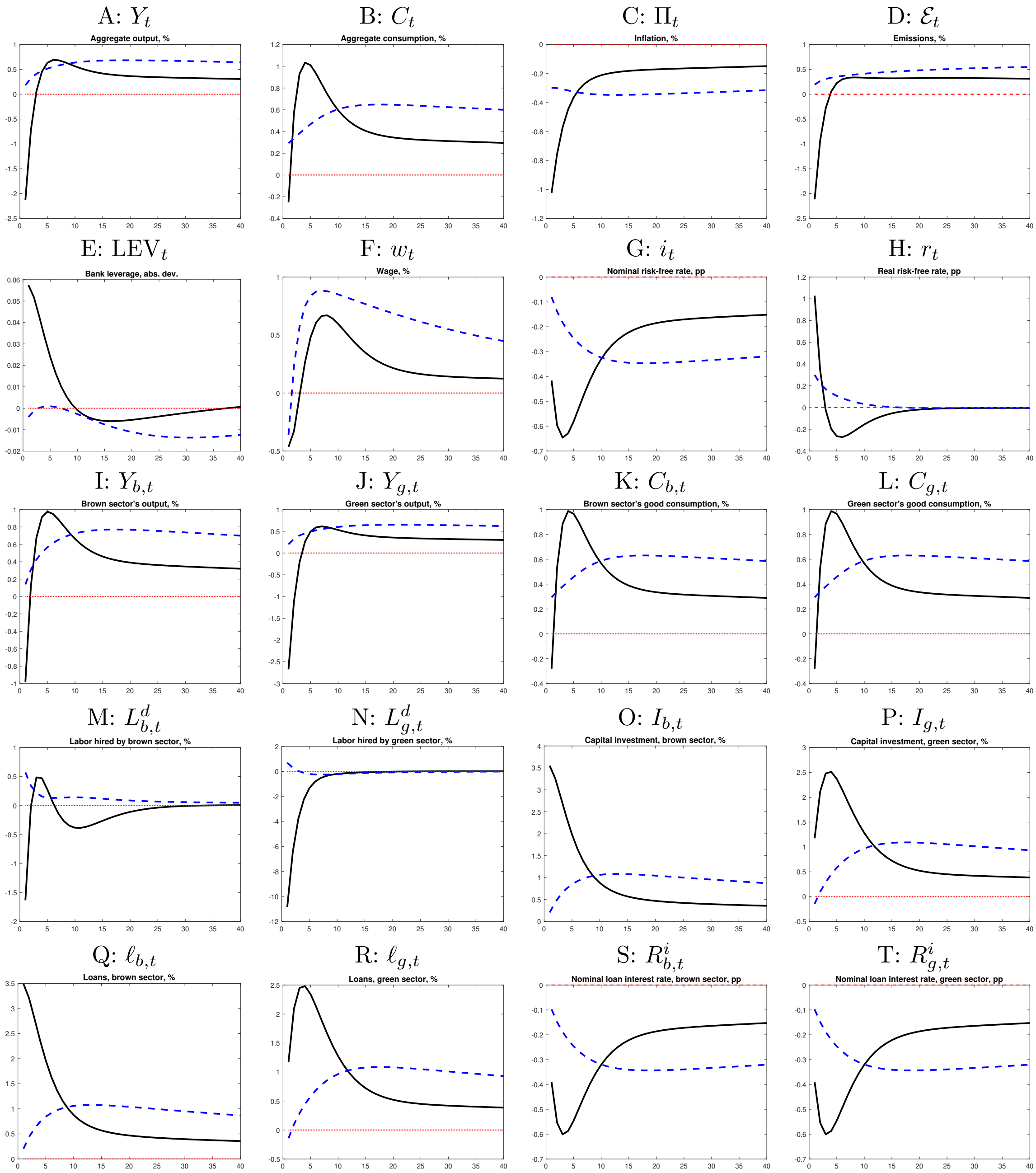
The form of revenue recycling significantly influences the magnitude of the responses to the carbon tax increase. While the general impact pattern of the carbon tax remains similar across different revenue recycling scenarios, several distinctions should be emphasised. Firstly, emission responses are qualitatively consistent across the three revenue recycling scenarios, with all policies yielding environmental improvements. However, due to the positive output effect of using the carbon tax revenues for building public green capital, the emissions decline is much smaller with this recycling scheme in place. Under the case where carbon tax revenue is used as a green investment subsidy, the responses of green and brown investments differ markedly compared to other scenarios. This results in increased loan demand in the green sectors and decreased loan demand in the brown sectors. Additionally, the negative output response can be overturned, at least in the short run. The investment subsidies lead to increased production of green goods which spills over to the brown sectors due to the input-output linkages. Consequently, both aggregate and sectoral consumption levels drop significantly compared to the other cases due to improved investment opportunities in the green sectors, prompting substitution incentives from consumption to investment, and the inflation surge. Similarly, utilising tax revenue to build green public capital emerges as the most effective policy in terms of output and inflation dynamics. In this scenario, there in an increase in output over the whole impulse response function horizon, inflation decreases in the medium run, and emissions are reduced for most of the impulse response function horizon. In the long run, the emissions at least do not increase significantly either.

No carbon tax scenario leads to a sizable increase in financial stability risks. With the lump-sum transfer scheme, bank leverage increases very mildly, but for the other two schemes we see financial stability improvements.

The possibility to abate emissions for intermediate goods producers present in the model substantially improves the economy's ability to reduce emissions in the response to carbon tax increases. With abatement present, a possible interpretation is that a fraction $\psi_{s,t}^A$ of firms in sector s do not produce any emissions while a fraction $1 - \psi_{s,t}^A$ of firms produce emissions subject to the sector-specific emissions intensity. Thereby, the distribution of carbon-neutral and carbon-intensive firms in each sector is endogenous and some firms in each sector switch to a carbon-neutral firm in response to carbon tax increases. In Appendix H, we report the effects of the carbon tax increase with different recycling schemes in the equivalent model where there is no possibility to abate emissions. We find that the emissions reductions become smaller by about 2% in this case without a significant effect on the impulse response functions of macroeconomic quantities.

Green technology and green public capital. Technological development, widespread adoption, and efficient implementation of innovative and environmentally friendly technologies are crucial elements for a successful transition to a low-carbon economy. In this analysis, we compare the effects of a standard positive total factor productivity shock in green sectors with those of an indirect productivity boost achieved through government investment in green public capital, as shown in Figure 5. Green public capital refers to government investments in infrastructure (e.g., updates to electricity distribution networks to bring renewable energy from the source to the users) and projects aimed at enhancing environmental sustainability and reducing carbon emissions. For instance, the Inflation Reduction Act of 2022 in the United States includes significant provisions for green public capital investments and seeks to address inflation and promote economic growth.

Figure 5: Impulse response functions – green technology shock, building public capital



Notes: This figure depicts impulse response functions for several different shocks in period 1. The black solid lines depict impulse response functions for an exogenous increase of 3.5 percentage points in the total factor productivity processes of the green sectors. The blue dashed lines correspond to the government issuing green public bonds for building public green capital in the amount of 5% of aggregate private investment.

The introduction of innovation in the green sectors leads to increased production only in the medium run. This growth is driven by higher investments across all sectors, with brown sector investments rising due to the demand for intermediate and capital inputs within the production network. As a result, loan demand increases in both green and brown sectors. Initially, there is a reduction in production volumes because fewer workers are hired in the green sectors as productivity is higher, thus requiring less labour inputs, and because of the fact that more intermediate inputs cannot be easily purchased due to supply constraints. However, sector-specific and aggregate consumption levels increase over the entire horizon, except for the initial few periods. On the inflation front, aggregate inflation decreases as expected due to the positive supply shock. To maintain equilibrium, the nominal interest rate decreases, offsetting the impact of reduced inflation and the initial decline in output. Unfortunately, there is no persistent decline in emissions; instead, emissions increase in the medium run. This is due to the positive effects of improved technology in the green sectors, which lead to higher demand for goods as intermediate and investment inputs from the brown sectors. Financial stability risks are slightly alleviated in the short to medium run due to the increase in loan amounts. In Appendix I, we simulate this scenario in a model without input-output linkages in the intermediate goods sectors and find a more positive effect of the green technology shock, especially for output.

When technological innovation in the green sector is implemented endogenously through building green public capital, the responses are notably different (blue dashed lines in Figure 5). We assume that the government finances the construction of public green capital by issuing green public bonds. This newly built green public capital directly enhances the production of green output. However, due to the interconnected investment and intermediate input network, we also observe an increase in brown output production. In this scenario, the increase in output does not immediately boost investments and loan demands. Instead, the rise in production leads to higher labour demand (Panels M and N). As wage costs increase (Panel F), there is an input reallocation from labour to capital, which subsequently boosts investment in both the brown and green sectors. Aggregate output increases alongside the rise in sectoral outputs, resulting in higher emissions. Inflation falls similarly to the previous case. While public capital has an expansionary impact on output, this leads to deflation, which is beneficial for the economy but detrimental to the environment. This is because green output production still relies heavily on goods from the brown sector. Financial stability risk is not considerably affected by this expansionary policy.

Brown investment tax / green investment subsidy. Brown investment taxes are designed to deter capital flows into activities that generate high levels of pollution, carbon emissions, or other harmful environmental effects. The objective is to make such investments less financially appealing, thereby redirecting capital towards cleaner and more sustainable alternatives. These taxes help internalise the external costs of environmentally damaging activities and provide a source of revenue for environmental protection and remediation efforts. Conversely, green investment subsidy policies offer financial incentives – such as tax credits or direct grants – to encourage investments in environmentally friendly projects, technologies, and industries. These subsidies aim to reduce the cost of capital for businesses and individuals investing in renewable energy, energy efficiency, sustainability, or other green initiatives. By making green investments more financially attractive, governments seek to accelerate the transition to a low-carbon economy. Green investment subsidies can stimulate innovation, create green jobs, and reduce greenhouse gas emissions, contributing to both economic growth and environmental protection.

Figure 6 illustrates the economic effects of a 5 percentage point increase in the investment tax rates for brown sectors (black solid lines) and an equivalent reduction in the green sectors' investment tax rates (blue dashed lines), effectively providing a subsidy for green investment starting in period 1. Additionally, the magenta dash-dotted lines depict a fiscally neutral combination of the two scenarios. In this case, a 5% capital investment subsidy is introduced for all green sectors, financed by increasing taxes on capital investments in the brown sectors, ensuring no change in the lump-sum tax collected from households.[12]

A 5 percentage point increase in the cost of investing in brown sectors' capital stocks results in a 15% decline in capital investment in the brown sectors, and we observe a significant reallocation to green investments under this policy choice. The loan demand falls for brown sectors and increases for green sectors. Initially, we do not observe a corresponding increase in green production despite the shift in investments. This is because green sectors' reliance on brown intermediate inputs causes cost increases also for the green sectors. Due to the higher costs of investments in the brown sectors, production levels in the brown sectors decline substantially. Consequently, aggregate output declines substantially. The increase in inflation due to the higher costs of brown investment prompts a monetary policy response, with the nominal interest rate being raised. Emissions decrease due the ensuing economic recession and financial stability risks become slightly alleviated in the aftermath of the investment tax shock.

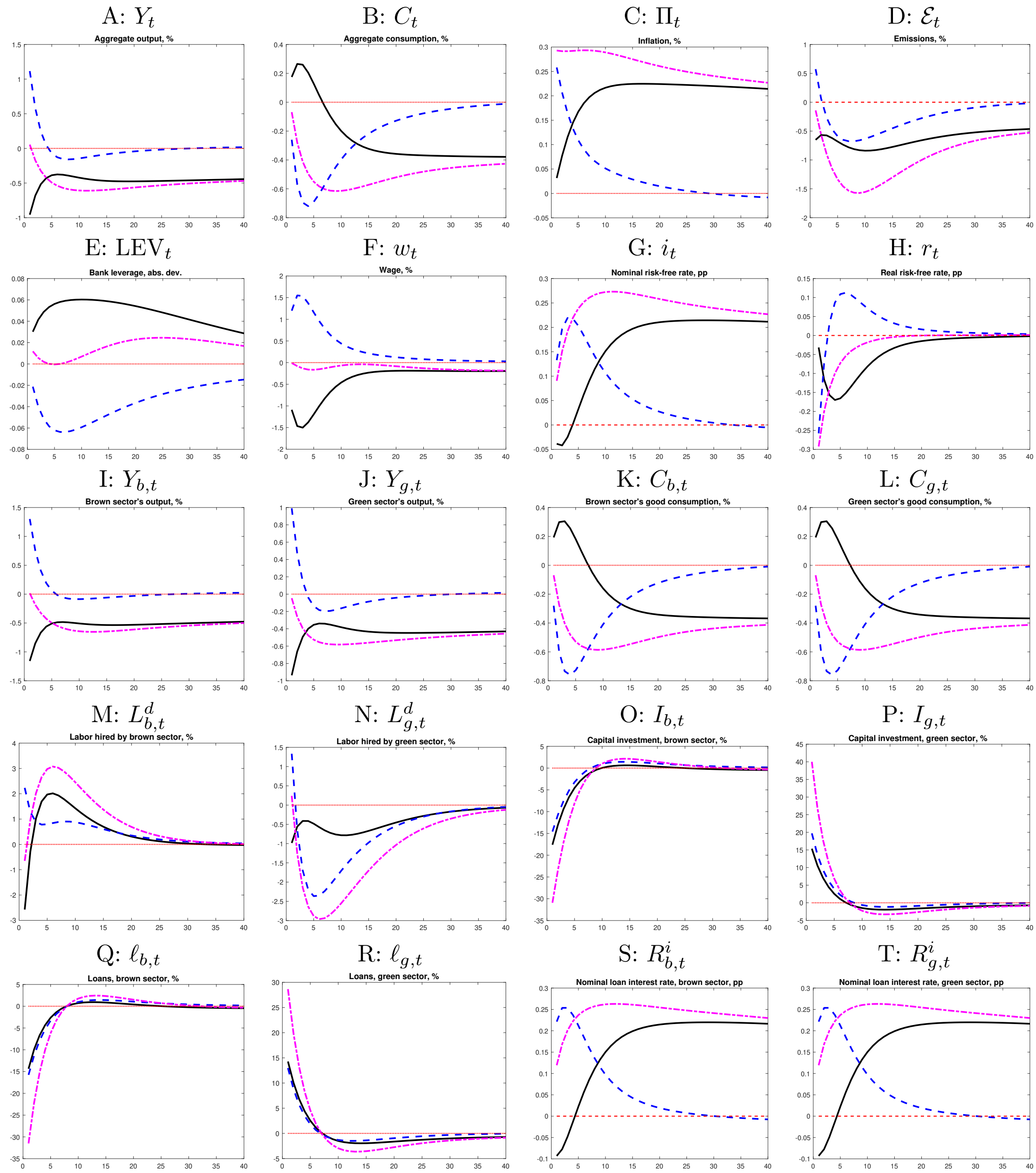
[12]The model is slightly modified for this scenario. Specifically, the exogenous processes for the capital investment taxes in the brown sectors (Equation 110 for those sectors s that are classified as green in Table E.2) are removed from the system of equations and replaced by the following endogenous termination of the capital investment tax rates in the brown sectors:

$$\sum_{s\in\mathcal{S}_g}[\tau^i_{s,t}P^i_{s,t}I_{s,t}] = -\left(\sum_{s\in\mathcal{S}_b}[\tau^i_{s,t}P^i_{s,t}I_{s,t}]\right),$$

$$\tau^i_{j,t} = \tau^i_{k,t}, \quad \forall\ j \neq k \in \mathcal{S}_b,$$

where $\mathcal{S}_g$ ($\mathcal{S}_b$) are the subsets of green (brown) sectors in our 37-sector economy.

Figure 6: Impulse response functions – investment tax/subsidy shocks



Notes: This figure depicts impulse response functions for exogenous changes in investment tax rates. The black solid lines correspond to the simulation that sees an exogenous increase of 5 percentage points in the investment tax rates of the brown sectors, while the blue dashed lines depict the economic effects of an exogenous decrease of 5 percentage points in the capital investment tax rates (i.e. an investment subsidy) of the green sectors in period 1. Finally, the magenta dash-dotted lines correspond to a fiscal budget-neutral combination of the two aforementioned simulations.

In a parallel scenario, we analyse the impact of a 5% increase in investment subsidies for the green sectors. The responses observed for both brown and green capital investment levels and loan demands are similar in both magnitude and direction to those in the previous investment tax case. The green sector benefits from investment subsidies and, due to the input-output linkages, so does the brown sector. Since the green investment subsidy is financed by debt issuance and an increase in the labour tax, the labour costs increase (Panel F). This leads to a small decrease in aggregate output in the medium run after an initial substantially positive response. As a result, emissions fall due to the drop in aggregate production in the medium run as well. Another reason is improved abatement efforts. Due to the relatively unchanged aggregate loan demand and the higher loan interest rates, financial stability improves by reducing bank leverage by about one half of an empirical standard deviation.

Finally, we explore a policy mix that combines the two previously discussed strategies. Specifically, we examine a scenario where financial incentives for green investments are funded by imposing an investment tax on brown investments. This approach maintains a fiscally neutral budget framework. We observe an immediate 40 percentage point increase in green capital investments. Conversely, as capital investments in the brown sectors become relatively less appealing, there is a 30 percentage point decline in these investments. The responses in sectoral loan demand levels mirror these investment trends. In this scenario, the labour income tax rate does not adjust and labour costs decrease mildly. However, the inflationary pressure caused by the higher financing costs (Panels S and T), fuelled by the higher demand for investments, constrains the economic benefits of this policy, as the monetary authority raises interest rates. Therefore, aggregate output and sectoral outputs fall. Also, consumption levels are reduced. The only good news is the reduced amount of emissions due to the lower production volumes.

As the discussion of the last scenario reveals, the presence of banks can change the dynamics of the economy after fiscal policy shocks. Therefore, Appendix J looks at a model variant where there are no banks. By redoing the fiscal policy scenarios in the model without banks and comparing the results with those reported in this section, we can shed light on the impact of the presence of banks in our model economy. We find that banks act as a shock smoothing device for shocks that directly affect investment and capital dynamics, while other scenarios are not significantly affected by the presence of banks (e.g., the scenario of increasing the consumption tax for brown goods whose figures for the benchmark model are reported in Appendix G). For a more elaborate discussion and the results of the model without banks, the reader is referred to Appendix J.

5 Conclusion

In this study, we introduce financial intermediaries into a multi-sector New-Keynesian E-DSGE model with input-output linkages via production and investment networks and monetary and fiscal authorities that can influence the economy via various conventional and unconventional monetary and fiscal policies. This allows us to study the role of the financial sector and its regulations in the context of the transition to a low-carbon economy, the main economic challenge of this century.

Specifically, we study the economic and environmental affects of sector-specific bank regulations via absconding rate shocks, sector-specific quantitative easing and tightening programmes, several carbon tax revenue recycling schemes, green technology innovations (exogenous productivity shocks vs public green capital build-up financed by public green bond issuance), and sector-specific investment tax and subsidy policies.

We find a tight link between developments in the green sectors and developments in the brown sectors due to the strong linkages via the production and investment networks. Therefore, almost all scenarios fail to induce a substantial green transition (decreasing fraction of high-emission production and increasing fraction of low-emission production) and both green and brown sectors either benefit or suffer from the policy implementation.

An increase in brown sectors' loan riskiness leads to more production and higher emissions while a decrease in green sectors' loan riskiness depresses output and leads to lower emissions. A combination of both these scenarios leads to a small increase in output and a very small decline in emissions. Similar observations hold for Green QE and Brown QT programmes.

While recycling carbon tax revenues in the form of a lump-sum transfer to households leads to a recession, using the carbon tax revenues to build public green capital alleviates the economic costs of higher carbon taxes completely and instead leads to a large economic expansion. Similarly, using the revenues to finance investment subsidies to green sectors implies a short-run economic boom, followed by a small recession in the medium run. In terms of environmental effects, for all recycling schemes we observe a considerable decline in emissions due to the increase in abatement efforts. Due to the increase in output of the building public green capital scheme, the emissions reduction is smaller in this case.

In a similar vein, building public green capital via issuing public green bonds to boost green sectors' productivity is superior to exogenous technology innovations in the green sectors. Introducing brown investment taxes is recessionary and good for the environment, while implementing green investment subsidies is expansionary in the short run and good for the environment in the medium to long run. Using brown investment taxes to finance green investment subsidies fails to solve this trade-off since the financing costs for the additional investments needed rise by too much.

Removing the input-output linkages in intermediate goods production or the financial intermediaries from the model, makes the carbon tax revenue recycling scheme of providing investment subsidies to green sectors the most expansionary policy in the short run while a recession is induced in the long run and this scheme still implies the largest emissions reduction. Without these input-output linkages, the pure investment tax and subsidy policies also work better.

Going forward, we will extend the model by one more financial asset: green corporate bonds. Green corporate bonds would be used to finance abatement efforts. Moreover, the aggregation rule for labour supply requires additional analysis.

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A Price Dispersion Law of Motion

Assuming that the capital-output ratio is the same for all firms within sector s, one also obtains that the intermediate inputs to output ratio and the labour to output ratio are the same for all firms within sector s, respectively. Furthermore, since the marginal cost function is the same for all firms within a sector in the symmetric equilibrium, one obtains that the production function is the same for each firm within sector s. Thus, we can simply integrate the individual firms' outputs into sectoral output to obtain, in conjunction with using Equation (32):

$$\mathring{Y}_{s,t} = \int_{\Phi_s} Y_{s,j,t}\, dj = (\mathring{P}_{s,t})^{-1}(1+K^p_{g,t})^{\alpha_{gs}} A_{s,t} \left(\zeta_s(\mathrm{VA}_{s,t})^{(\sigma_s-1)/\sigma_s} + (1-\zeta_s)(Z_{s,t})^{(\sigma_s-1)/\sigma_s}\right)^{\sigma_s/(\sigma_s-1)}, \tag{A.1}$$

where $\mathring{P}_{s,t} = \int_{\Phi_s}(P_{s,j,t}/P_{s,t})^{-\theta}\, dj$ is the price dispersion term. Given that a fraction κ_s of firms cannot adjust its prices for the next period, whereas the other firms (with mass $1-\kappa_s$) will re-optimise the next period, the dynamics of the dispersion term are as follows:

$$\begin{aligned}
\mathring{P}_{s,t+1} &= \kappa_s \int_{\Phi_s} \left(\frac{P_{s,j,t}}{P_{s,t+1}}\right)^{-\theta} dj + (1-\kappa_s)\left(\frac{P^*_{s,t+1}}{P_{s,t+1}}\right)^{-\theta} \\
&= \kappa_s \int_{\Phi_s} \left(\frac{P_{s,t}}{P_{s,t+1}}\right)^{-\theta}\left(\frac{P_{s,j,t}}{P_{s,t}}\right)^{-\theta} dj + (1-\kappa_s)\left(\frac{P^*_{s,t+1}}{P_{s,t+1}}\right)^{-\theta} \\
&= \kappa_s \left(\frac{P_{s,t+1}}{P_{s,t}}\right)^{\theta} \int_{\Phi_s} \left(\frac{P_{s,j,t}}{P_{s,t}}\right)^{-\theta} dj + (1-\kappa_s)\left(\frac{P^*_{s,t+1}}{P_{s,t+1}}\right)^{-\theta} \\
&= \kappa_s \left(\frac{P_{s,t+1}}{P_{s,t}}\right)^{\theta} \mathring{P}_{s,t} + (1-\kappa_s)\left(\frac{P^*_{s,t+1}}{P_{s,t+1}}\right)^{-\theta},
\end{aligned} \tag{A.2}$$

which – using real variables and lagging above equation by one period – becomes:

$$\mathring{P}_{s,t} = \kappa_s \left(\frac{p_{s,t}\Pi_t}{p_{s,t-1}}\right)^{\theta} \mathring{P}_{s,t-1} + (1-\kappa_s)\left(\frac{p_{s,t}}{p^*_{s,t}}\right)^{\theta}. \tag{A.3}$$

B Normalisation of the Model

Most equations in the main text are given in nominal terms. For defining the equilibrium of the model, we need to derive the real variant of all equations. Thus, in the following we normalise the model by denoting and defining the real version of a variable as follows: $p_t = P_t/\mathcal{P}_t$, where P_t is a generic nominal variable as a placeholder for all nominal variables used in the main text and the aggregate price index $\mathcal{P}_t$ is used to make nominal variables real. The nominal marginal utility of consumption $\lambda_{h,t}$ is made real by multipliying it with $\mathcal{P}_t$, where real marginal utility of consumption is denoted by $\widetilde{\lambda}_{h,t}$.

However, when we normalise portfolio holdings like deposits of loan amounts we normalise by the lagged price level, e.g., $d_t = D_t/\mathcal{P}_{t-1}$.

The following list of equations comprises the equations requiring the normalisation of nominal prices. Other equations, not listed here, are used as given in the main text in the implementation of the model.

- Real sectoral consumption choice of households

$$(1+\tau^c_{s,t})p_{s,t}C_{s,t} = p^c_t \omega_{cs} C_t, \quad s = 1, \ldots, S \tag{B.1}$$

- Real price of consumption

$$p^c_t = \prod_{s=1}^{S} [(1+\tau^c_{s,t})p_{s,t}]^{\omega_{cs}} \tag{B.2}$$

- Real budget constraint of households

$$\begin{aligned} p^c_t C_t + d_{t+1} + \Phi_t = r^d_{t-1} d_t + (1-\tau^W_t)\sum_{s=1}^{S} w_{s,t} L^d_{s,t} + \sum_{s=1}^{S}(z^Y_{s,t} + z^y_{s,t} + z^k_t) \\ + z^C_t + z^Y_t + z^b_t + (1-\theta)\mathrm{nw}_{t-1}(\Pi_t)^{-1} + t_t \end{aligned} \tag{B.3}$$

- Real deposits Euler equation

$$1 = \mathbb{E}_t[\mathbb{M}_{t,t+1} \cdot R^d_t/\Pi_{t+1}] = \mathbb{E}_t[\mathbb{M}_{t,t+1} r^d_{t+1}] \tag{B.4}$$

- Real deposit interest rate

$$r^d_t = R^d_{t-1}/\Pi_t \tag{B.5}$$

- Marginal utility of consumption

$$\widetilde{\lambda}_{h,t} = \lambda_{h,t}\mathcal{P}_t = \frac{1}{p_t^c}\left(C_t - \frac{\chi(L_t)^{1+1/f}}{1+1/f}\right)^{-1/\psi} \tag{B.6}$$

- Nominal stochastic discount factor

$$\mathbb{M}^{\$}_{t,t+1} = \beta\widetilde{\lambda}_{h,t+1}/\widetilde{\lambda}_{h,t} \cdot \Pi_{t+1} \tag{B.7}$$

- Real stochastic discount factor

$$\mathbb{M}_{t,t+1} = \beta\widetilde{\lambda}_{h,t+1}/\widetilde{\lambda}_{h,t} \tag{B.8}$$

- Consumer price inflation

$$\Pi^c_{t+1} = p^c_{t+1}/p^c_t \cdot \Pi_{t+1} \tag{B.9}$$

- Real aggregate consumption goods firm profits:

$$z_t^C = p_t^c C_t - \sum_{s=1}^{S}(1+\tau^c_{s,t})p_{s,t}C_{s,t} \tag{B.10}$$

- Real sectoral wage evolution process ($s = 1, \ldots, S$)

$$w_{s,t} = \left((1-\kappa_{\ell s})(w^*_{s,t})^{1-\theta_{\ell s}} + \kappa_{\ell s}(w_{s,t-1}/\Pi_t)^{1-\theta_{\ell s}}\right)^{1/(1-\theta_{\ell s})} \tag{B.11}$$

- Aggregate real wage definition

$$w_t L_t^d = \sum_{s=1}^{S} w_{s,t}L^d_{s,t} \tag{B.12}$$

- Wage dispersion process ($s = 1, \ldots, S$)

$$\Theta^W_{s,t} = (1-\kappa_{\ell s})\left(\frac{w^*_{s,t}}{w_{s,t}}\right)^{-\theta_{\ell s}} + \kappa_{\ell s}\left(\frac{w_{s,t-1}}{w_{s,t}\Pi_t}\right)^{-\theta_{\ell s}}\Theta^W_{s,t-1} \tag{B.13}$$

- Optimal wage equilibrium auxiliary variable 1 ($s = 1, \ldots, S$)

$$g_{s,1,t} = \frac{\theta_{\ell s}\chi\widetilde{\lambda}_{h,t}p_t^c}{\theta_{\ell s}-1}(L_t^d)^{1/f}\left(\frac{w^*_{s,t}}{w_{s,t}}\right)^{-\theta_{\ell s}} L^d_{s,t} + \beta\kappa_{\ell s}\mathbb{E}_t\left[\left(\frac{w^*_{s,t}}{w^*_{s,t+1}\Pi_{t+1}}\right)^{-\theta_{\ell}} g_{s,1,t+1}\right] \tag{B.14}$$

- Optimal wage equilibrium auxiliary variable 2 ($s = 1, \dots, S$)

$$g_{s,2,t} = (1-\tau_t^W)\widetilde{\lambda}_{h,t}\left(\frac{w_{s,t}^*}{w_{s,t}}\right)^{-\theta_{\ell s}} w_{s,t}^* L_{s,t}^d + \beta\kappa_{\ell s}\mathbb{E}_t\left[\left(\frac{w_{s,t}^*}{w_{s,t+1}^*\Pi_{t+1}}\right)^{1-\theta_{\ell s}} g_{s,2,t+1}\right]. \tag{B.15}$$

- Real aggregate final goods firm profits:

$$z_t^Y = Y_t - \sum_{s=1}^{S} p_{s,t}Y_{s,t} \tag{B.16}$$

- Real sectoral final goods firm profits ($s = 1, \dots, S$)

$$z_{s,t}^Y = p_{s,t}Y_{s,t} - \int_{\Phi_s} p_{s,j,t}Y_{s,j,t}\, dj \tag{B.17}$$

- Real sectoral intermediate input price

$$p_t^s = \prod_{r=1}^{S} p_{r,t}^{\omega_{sr}}, \quad s = 1, \dots, S \tag{B.18}$$

- Aggregate price index / aggregate inflation

$$1 = \prod_{s=1}^{S}\left(\frac{p_{s,t}}{\Omega_{s,t}}\right)^{\omega_{ys}} \tag{B.19}$$

- Intermediate goods firms' intermediate inputs decisions

$$p_{r,t}Z_{s,t}(r) = p_t^s\omega_{sr}Z_{s,t}, \quad r = 1, \dots, S, \quad s = 1, \dots, S \tag{B.20}$$

- Intermediate goods firms' cost minimisation w.r.t. labour ($s = 1, \dots, S$)

$$w_{s,t} = \mathrm{mc}_{s,t}(Y_{s,t})^{1/\sigma_s}(A_{s,t}(1+K_{g,t}^p)^{\alpha_{gs}}))^{1-\sigma_s}\zeta_s(\mathrm{VA}_{s,t})^{1/\gamma_s-1/\sigma_s}(1-\alpha_s)(L_{s,t}^d)^{-1/\gamma_s} \tag{B.21}$$

- Intermediate goods firms' cost minimisation w.r.t. intermediate inputs ($s = 1, \dots, S$)

$$(1+\tau_{s,t}^z)p_t^s = \mathrm{mc}_{s,t}(Y_{s,t})^{1/\sigma_s}(A_{s,t}(1+K_{g,t}^p)^{\alpha_{gs}}))^{1-\sigma_s}(1-\zeta_s)(Z_{s,t})^{-1/\gamma_s} \tag{B.22}$$

- Intermediate goods firms' cost minimisation w.r.t. capital ($s = 1, \dots, S$)

$$r_{s,t}^k = \mathrm{mc}_{s,t}(Y_{s,t})^{1/\sigma_s}(A_{s,t}(1+K_{g,t}^p)^{\alpha_{gs}}))^{1-\sigma_s}\zeta_s(\mathrm{VA}_{s,t})^{1/\gamma_s-1/\sigma_s}\alpha_s(u_{s,t}K_{s,t})^{-1/\gamma_s}u_{s,t} \tag{B.23}$$

- Abatement rate determination:

$$\psi^A_{s,t} = \left(\frac{\tau^F_{s,t}}{p_{s,t}} \frac{\nu_s}{\iota_{2s}\iota_{3s}} \right)^{1/(\iota_{3s}-1)}, \quad s = 1, \ldots, S \tag{B.24}$$

- Intermediate goods firm profits ($s = 1, \ldots, S$)

$$z^y_{s,t} = \int_{\Phi_s} \left(p_{s,j,t} Y_{s,j,t} - w_{s,t} L^d_{s,j,t} - r^k_{s,t} K_{s,j,t} - (1+\tau^z_{s,t}) p^s_t Z_{s,j,t} - \tau^F_{s,t} \nu_s (1-\psi^A_{s,j,t}) Y_{s,j,t} - p_{s,t} X^A_{s,j,t} \right) dj \tag{B.25}$$

- Optimal price equilibrium

$$p^*_{s,t} = (f_{1,s,t} + f_{3,s,t})/f_{2,s,t}, \quad s = 1, \ldots, S \tag{B.26}$$

- Third auxiliary variable in optimal price equilibrium

$$f_{3,s,t} = \mu \left(\frac{Y_{s,t}}{\omega_{ys} Y_t} \right)^{-\theta} [p_{s,t}\iota_{2s}(\psi^A_{s,t})^{\iota_{3s}} + \tau^F_{s,t}\nu_s(1-\psi^A_{s,t})] Y_{s,t} + \kappa_s \mathbb{E}_t[\mathbb{M}_{t,t+1}(\Pi_{t+1})^\theta f_{3,s,t+1}] \tag{B.27}$$

- Intermediate goods price dynamics

$$(p_{s,t})^{1-\theta} = \kappa_s \left(p_{s,t-1}/\Pi_t\right)^{1-\theta} + (1-\kappa_s)(p^*_{s,t})^{1-\theta}, \quad s = 1, \ldots, S \tag{B.28}$$

- Price dispersion dynamics

$$\mathring{P}_{s,t} = \kappa_s \left(p_{s,t}\Pi_t/p_{s,t-1}\right)^\theta \mathring{P}_{s,t-1} + (1-\kappa_s)\left(p_{s,t}/p^*_{s,t}\right)^\theta \tag{B.29}$$

- Real capital producer profits

$$z^k_{s,t} = r^k_{s,t} K_{s,t} - (1+\tau^i_{s,t}) p^i_{s,t} I_{s,t} + \ell^i_{s,t+1} - r^i_{s,t}\ell^i_{s,t} \tag{B.30}$$

- Real capital producer value ($s = 1, \ldots, S$)

$$v^k_{s,t} = \mathbb{E}_t \left[\sum_{n=0}^{\infty} \mathbb{M}_{t,t+n} \left(r^k_{s,t+n} K_{s,t+n} - (1+\tau^i_{s,t}) p^i_{s,t+n} I_{s,t+n} + \ell^i_{s,t+n+1} - r^i_{s,t+n}\ell^i_{s,t+n} \right) \right] \tag{B.31}$$

- Real loan-in-advance constraint of capital producers in each sector $s = 1, \ldots, S$ (after noting that this condition will bind in equilibrium)

$$\ell^i_{s,t+1} = \chi_s (1+\tau^i_{s,t}) p^i_{s,t} I_{s,t} \tag{B.32}$$

- Capital real marginal Tobin's Q ($s = 1, \ldots, S$)

$$q_{s,t} = (1+\mu^{\mathtt{LIA}}_{s,t}\chi_s)(1+\tau^i_{s,t}) p^i_{s,t}/\Lambda'_{s,t} \tag{B.33}$$

- Capital Euler equation $(s = 1, \dots, S)$

$$q_{s,t} = \mathbb{E}_t\left[\mathbb{M}_{t,t+1}\left(r^k_{s,t+1} - \frac{q_{s,t+1}\Lambda'_{s,t+1}I_{s,t+1}}{K_{s,t+1}} + q_{s,t+1}(\Lambda_{s,t+1} + 1 - \delta_s)\right)\right] \tag{B.34}$$

- Sectoral investment good price $(s = 1, \dots, S)$

$$p^i_{s,t} = \prod_{r=1}^{S}(p_{r,t})^{\omega^i_{sr}}, \quad s = 1, \dots, S. \tag{B.35}$$

- Investment goods producers' first order conditions $(r, s = 1, \dots, S)$

$$p_{r,t}I_{s,t}(r) = p^i_{s,t}\omega^i_{sr}I_{s,t}. \tag{B.36}$$

- Real lump-sum tax

$$t_t = \sum_{s=1}^{S}\left[\tau^F_{s,t}\nu_s(1 - \psi^A_{s,t})\mathring{Y}_{s,t}\right] \tag{B.37}$$

- Real government budget constraint

$$\begin{aligned} r^b_{b,t}b_{b,t} + r^b_{g,t}b_{g,t} + \sum_{s=1}^{S}G_{s,t} = t_{cb} + b_{b,t+1} + b_{g,t+1} + \tau^W_t\sum_{s=1}^{S}w_{s,t}L^d_{s,t} \\ + \sum_{s=1}^{S}\left[\tau^c_{s,t}p_{s,t}C_{s,t} + \tau^z_{s,t}p^s_tZ_{s,t} + \tau^i_{s,t}p^i_{s,t}I_{s,t}\right] \end{aligned} \tag{B.38}$$

- Real sectoral public consumption choice of the fiscal authority

$$p_{s,t}G_{s,t} = p^g_t\omega_{gs}G_t, \quad s = 1, \dots, S. \tag{B.39}$$

- Real aggregate public consumption expenditure determination

$$p^g_tG_t = \bar{g}Y_t. \tag{B.40}$$

- Real price of aggregate public consumption bundle

$$p^g_t = \prod_{s=1}^{S}p^{\omega_{gs}}_{s,t}. \tag{B.41}$$

- Real public green bond issuance

$$b_{g,t+1} = s^b_{g,t}p^i_tI_t. \tag{B.42}$$

- Real monetary authority balance sheet

$$\mathrm{re}_t = b_{b,t}^{cb} + b_{g,t}^{cb} + \sum_{s=1}^{S} \ell_{s,t}^{i,cb}. \tag{B.43}$$

- Public general bond purchases of the monetary authority

$$b_{b,t}^{cb} = s_{b,t}^{cb} b_{b,t}. \tag{B.44}$$

- Public green bond purchases of the monetary authority

$$b_{g,t}^{cb} = s_{g,t}^{cb} b_{g,t}. \tag{B.45}$$

- Real sectoral corporate bond purchases of the monetary authority

$$\ell_{s,t}^{i,cb} = s_{\ell,s,t}^{cb} \ell_{s,t}^{i}, \quad s = 1, \ldots, S. \tag{B.46}$$

- Real transfer of the profits of the monetary authority to the government

$$t_{cb,t} = r_{b,t}^{b} b_{b,t}^{cb} + r_{g,t}^{b} b_{g,t}^{cb} + \sum_{s=1}^{S} (r_{s,t}^{i} \ell_{s,t}^{i,cb}) - r_t \mathrm{re}_t. \tag{B.47}$$

- Real bank balance sheet

$$\mathrm{nw}_t + d_t = \mathrm{re}_{t+1} + b_{b,t+1}^{p} + b_{g,t+1}^{p} + \sum_{s=1}^{S} \ell_{s,t+1}^{i,p} \tag{B.48}$$

- Real aggregate bank net worth accumulation

$$\mathrm{nw}_t = \theta \left(\frac{\sum_{s=1}^{S} (r_{s,t}^{i} - r_t^{d}) \ell_{s,t}^{i,p}}{\mathrm{nw}_{t-1}} + \frac{(r_{b,t}^{b} - r_t^{d}) b_{b,t}^{p} + (r_{g,t}^{b} - r_t^{d}) b_{g,t}^{p}}{\mathrm{nw}_{t-1}} + \frac{(r_t - r_t^{d}) \mathrm{re}_t}{\mathrm{nw}_{t-1}} + r_t^{d} \right) \mathrm{nw}_{t-1} + \Phi_{t-1}. \tag{B.49}$$

- Incentive compatibility constraint in real terms (after imposing bank symmetry and noting that this condition will bind in equilibrium)

$$\upsilon_t \cdot \mathrm{nw}_t = \Delta_{bb} b_{b,t+1}^{p} + \Delta_{bg} b_{g,t+1}^{p} + \sum_{s=1}^{S} \Delta_{s,t} \ell_{s,t+1}^{i,p} \tag{B.50}$$

- Real bank start-up fund

$$\Phi_t = \varphi \cdot \mathrm{nw}_t \tag{B.51}$$

- Real public general bond interest rate

$$r^b_{b,t} = R^b_{b,t-1}/\Pi_t. \tag{B.52}$$

- Real public green bond interest rate

$$r^b_{g,t} = R^b_{g,t-1}/\Pi_t. \tag{B.53}$$

- Real sectoral loan interest rate

$$r^i_{s,t} = R^i_{s,t-1}/\Pi_t, \quad s = 1, \ldots, S. \tag{B.54}$$

- Real flow of funds from banks

$$\begin{aligned} z^b_t = & \sum_{s=1}^{S}(r^i_{s,t}\ell^i_{s,t} - \ell^{i,p}_{s,t+1}) + r^b_{b,t}b^p_{b,t} - b^p_{b,t+1} + r^b_{g,t}b^p_{g,t} - b^p_{g,t+1} + r_t\mathrm{re}_t - \mathrm{re}_{t+1} \\ & + d_{t+1} - r^d_t d_t + \Phi_t - (1-\theta)\mathrm{nw}_{t-1}(\Pi_t)^{-1}, \end{aligned} \tag{B.55}$$

- Real sectoral resource constraints

$$\mathring{Y}_{s,t} = G_{s,t} + C_{s,t} + \iota_{2s}(\psi^A_{s,t})^{\iota_{3s}}\mathring{Y}_{s,t} + \sum_{r=1}^{S} I_{r,t}(s) + \sum_{r=1}^{S} Z_{r,t}(s), \quad s = 1, \ldots, S \tag{B.56}$$

- Real aggregate resource constraint

$$Y_t = \sum_{s=1}^{S} p_{s,t}\mathring{Y}_{s,t} = p^g_t G_t + p^c_t C_t + \sum_{s=1}^{S}\left[p^i_{s,t}I_{s,t} + p_{s,t}\iota_{2s}(\psi^A_{s,t})^{\iota_{3s}}\mathring{Y}_{s,t} + p^s_t Z_{s,t}\right] \tag{B.57}$$

- Real public general bond market clearing

$$b_{b,t} = b^p_{b,t} + b^{cb}_{b,t}. \tag{B.58}$$

- Real public general bond market clearing

$$B_{g,t} = B^p_{g,t} + B^{cb}_{g,t} \tag{B.59}$$

- Real public general bond market clearing

$$\ell^i_{s,t+1} = \ell^{i,p}_{s,t+1} + \ell^{i,cb}_{s,t+1}, \quad s = 1, \ldots, S. \tag{B.60}$$

C Definition of Equilibrium

The equilibrium system is composed of $\mathbf{2S^2 + 43S + 39}$ **variables** and $\mathbf{2S^2 + 43S + 39}$ **equations** in total, which can be broken down by sectors in the following way:

1. In the households sector, the real price of the consumption bundle p_t^c, consumer price inflation Π_t^c, the consumption bundle C_t, sectoral consumption levels $\{C_{s,t}\}_{s=1}^S$, total aggregate labour supply L_t, sectoral labour supplies $\{L_{s,t}\}_{s=1}^S$, total aggregate labour demand by firms L_t^d, the real aggregate wage w_t, real sectoral wages $\{w_{s,t}\}_{s=1}^S$, optimal real sectoral wages $\{w_{s,t}^*\}_{s=1}^S$, the sectoral wage distortion processes $\{\theta_{s,t}^W\}_{s=1}^S$, the auxiliary variables $\{g_{s,1,t}\}_{s=1}^S$ and $\{g_{s,2,t}\}_{s=1}^S$, real marginal utility of consumption $\widetilde{\lambda}_{h,t}$, the nominal household stochastic discount factor $\mathbb{M}_{t,t+1}^{\$}$, and the real household stochastic discount factor $\mathbb{M}_{t,t+1}$, and real one-period deposit holdings d_t – **in total, $\mathbf{7S + 10}$ variables** – are chosen such that the consumption goods producers and labour unions maximise their profits and the representative household maximises its lifetime utility, subject to several market clearing conditions, which implies that the following equilibrium conditions need to hold: (12), (17), (19), (114), (B.1), (B.2), (B.4), (B.6), (B.7), (B.8), (B.9), (B.11), (B.12), (B.13), (B.14), (B.15) – **in total, $\mathbf{7S + 9}$ equations**.

2. In the final and intermediate goods sectors, the intermediate goods firms choose their demands for production inputs (labour $\{L_{s,t}^d\}_{s=1}^S$, intermediate inputs $\{Z_{s,t}\}_{s=1}^S$, and private sectoral capital $\{K_{s,t}\}_{s=1}^S$ to determine real sectoral price indices $\{p_{s,t}\}_{s=1}^S$, aggregate inflation rate Π_t, real marginal cost functions $\{\mathrm{mc}_{s,t}\}_{s=1}^S$, and real private sectoral capital returns $\{r_{s,t}^k\}_{s=1}^S$, the intermediate goods producers also choose their optimal real relative price levels $\{p_{s,t}^*\}_{s=1}^S$ giving rise to the auxiliary variables $\{f_{1,s,t}\}_{s=1}^S$, $\{f_{2,s,t}\}_{s=1}^S$, and $\{f_{3,s,t,}\}_{s=1}^S$, given the choices of the sectoral final goods firms for intermediate goods to determine sectoral final goods output $\{Y_{s,t}\}_{s=1}^S$ (before price distortion), $\{\mathring{Y}_{s,t}\}_{s=1}^S$ (after price distortion), value-added $\{\mathrm{VA}_{s,t}\}_{s=0}^S$, and price distortion levels $\{\mathring{P}_{s,t}\}_{s=1}^S$, while the intermediate inputs producers choose their production outputs $\{Z_{s,t}(r)\}_{r,s=1}^S$ to determine real intermediate inputs prices $\{p_t^s\}_{s=1}^S$ and abatement rates $\{\psi_{s,t}^A\}_{s=0}^S$ to determine abatement investments $\{X_{s,t}^A\}_{s=0}^S$ and the capital utilisation rates $\{u_{s,t}\}_{s=1}^S$, which are subject to exogenous processes – **in total, $\mathbf{S^2 + 18S + 1}$ variables** – which implies that the following equilibrium conditions need to hold: (33), (34), (35), (45), (58), (59), (61), (B.18), (B.19), (B.20), (B.21), (B.22), (B.23), (B.24), (B.26), (B.27), (B.28), (B.29) – **in total, $\mathbf{S^2 + 16S + 1}$ equations**.

3. In the capital production sectors, the capital producers produce profit-maximizing sectoral capital supplies while being subject to capital adjustment costs $\{\Lambda_{s,t}\}_{s=1}^S$ and its derivative $\{\Lambda'_{s,t}\}_{s=1}^S$, and they maximise the real capital producer firm values

$\{v^k_{s,t}\}_{s=1}^S$, subject to loan-in-advance constraints, by choosing investment demands $\{I_{s,t}\}_{s=1}^S$ and the next period's capital demands so that the real investment good shadow prices $\{q_{s,t}\}_{s=1}^S$ and loan-in-advance constraint shadow prices $\{\mu^{\mathtt{LIA}}_{s,t}\}_{s=1}^S$ are determined – **in total, 6S variables** – which implies that these sectors obey the following equilibrium conditions: (63), (64), (75), (76), (B.31), (B.32), (B.33), (B.34) – **in total, 8S equations**.

4. In the investment goods production sectors, the investment goods producers choose their production outputs $\{I_{s,t}(r)\}_{r,s=1}^S$ to determine real investment goods prices $\{p^i_{s,t}\}_{s=1}^S$ – **in total, $\mathbf{S^2 + S}$ variables** – which implies that these sectors obey the following equilibrium conditions: (B.35), (B.36) – **in total, $\mathbf{S^2 + S}$ equations**.

5. Environmental accounting defines total emissions $\mathcal{E}_t$ and the stock of carbon emissions above pre-industrial levels M_t, which lead to damages in the intermediate goods sector $\{\Omega_{s,t}\}_{s=1}^S$ – **in total, $\mathbf{S + 2}$ variables** – governed by equations: (25), (111), (112) – **in total, $\mathbf{S + 2}$ equations**.

6. In the banking sector, the banks choose net worth levels to arrive at an aggregate net worth level nw_t, public general bond holdings $b^p_{b,t}$, public green bond holdings $b^p_{g,t}$, sectoral corporate loan amounts $\{\ell^{i,p}_{s,t}\}_{s=1}^S$ to maximise their value v_t, subject to the incentive compatibility constraint with sector-specific absconding rates $\{\Delta_{s,t}\}_{s=1}^S$, the bank balance sheet, the nominal deposit rate R^d_t equality to the monetary policy rate, and the amount of the bank start-up fund by the households Φ_t which gives rise to the bank adjustment to the stochastic discount factor Ω_t, the shadow price to alleviate the incentive compatibility constraint $\mu^{\mathtt{icc}}_t$, the real deposit interest rate r^d_t, the real public general bond return $r^b_{b,t}$, the real public green bond return $r^b_{g,t}$, and the real sectoral loan returns $\{r^i_{s,t}\}_{s=1}^S$ – **in total, $\mathbf{3S + 11}$ variables** – and the following equilibrium conditions: (81), (82), (83), (84), (85), (89), (92), (B.5), (B.48), (B.49), (B.50), (B.51) – **in total, $\mathbf{2S + 10}$ equations**;

7. In the public sector (fiscal and monetary authority), the nominal risk-free interest rate i_t, the real risk-free interest rate r_t, the real lump-sum tax transfer t_t, sectoral public consumption $\{G_{s,t}\}_{s=1}^S$, aggregate public consumption G_t, the real price of aggregate public consumption p^g_t, the real transfer from the monetary authority to the fiscal authority t_{cb}, the real aggregate sectoral loan amounts $\{\ell^i_{s,t}\}_{s=1}^S$, the fiscal authority's issuance of real public general and green bonds $b_{b,t}$ and $b_{g,t}$, the monetary authority's real holdings of public general bonds $b^{cb}_{b,t}$, public green bonds $b^{cb}_{g,t}$, and sectoral corporate bonds $\{\ell^{i,cb}_{s,t}\}_{s=1}^S$, real central bank reserves re_t, the green public capital $K^p_{g,t}$, and the tax rates τ^W_t, $\{\tau^c_{s,t}\}_{s=1}^S$, $\{\tau^z_{s,t}\}_{s=1}^S$, $\{\tau^i_{s,t}\}_{s=1}^S$, $\{\tau^F_{s,t}\}_{s=1}^S$ – **in total, $\mathbf{7S + 13}$ variables** – have to obey the following laws of motion, market clearing conditions, and equations: (90), (91), (100), (102), (108), (109), (110),

(113), (B.37), (B.38), (B.39), (B.40), (B.41), (B.42), (B.43), (B.44), (B.45), (B.46), (B.47), (B.58), (B.59), (B.60) – **in total, $\mathbf{7S + 15}$ equations**.

8. For the aggregate economy, there is a homogeneous total factor productivity shock A_t and an aggregate final goods firm aggregates sectoral outputs to aggregate output (GDP) Y_t – **in total, 2 variables** – such that the following productivity law of motion, the aggregate resource constraint, and the sectoral resource constraints hold: (36), (B.56), (B.57) – **in total, $\mathbf{S + 2}$ equations**.

D Steady State Equations

In this appendix, we derive the steady state equation system of our model.

D.1 Representative household

At steady state, the household equilibrium via Equations (12), (17), (19), (114), (B.1), (B.2), (B.4), (B.6), (B.7), (B.8), (B.9), (B.11), (B.12), (B.13), (B.14), and (B.15) becomes:

$$\Theta_s^W = \frac{(1-\kappa_{\ell s})\left(w_s^*/w_s\right)^{-\theta_{\ell s}}}{1-\kappa_{\ell s}(\bar{\Pi})^{\theta_{\ell s}}}, \quad s=1,\ldots,S, \tag{D.1}$$

$$L_s = \Theta_s^W L_s^d, \quad s=1,\ldots,S, \tag{D.2}$$

$$L = \sum_{s=1}^{S} L_s, \tag{D.3}$$

$$L^d = \sum_{s=1}^{S} L_s^d, \tag{D.4}$$

$$w = \left(\sum_{s=1}^{S} w_s L_s^d\right)/L^d, \tag{D.5}$$

$$(1+\bar{\tau}_s^c)p_s C_s = p^c \omega_{cs} C, \quad s=1,\ldots,S, \tag{D.6}$$

$$p^c = \prod_{s=1}^{S}[(1+\bar{\tau}_s^c)p_s]^{\omega_{cs}}, \tag{D.7}$$

$$w_s^*/w_s = \left(\frac{1-\kappa_{\ell s}(\bar{\Pi})^{\kappa_{\ell s}-1}}{1-\kappa_{\ell s}}\right)^{1/(1-\theta_{\ell s})}, \quad s=1,\ldots,S, \tag{D.8}$$

$$g_{s,1} = g_{s,2}, \quad s=1,\ldots,S, \tag{D.9}$$

$$g_{s,1} = \frac{\theta_{\ell s}\chi\widetilde{\lambda}_h p^c}{\theta_{\ell s}-1}(L^d)^{1/f}L_s^d/(1-\beta\kappa_{\ell s}(\bar{\Pi})^{\theta_{\ell s}}), \quad s=1,\ldots,S, \tag{D.10}$$

$$g_{s,2} = (1-\tau^W)\widetilde{\lambda}_h w_s^* L_s^d/(1-\beta\kappa_{\ell s}(\bar{\Pi})^{\theta_{\ell s}-1}), \quad s=1,\ldots,S, \tag{D.11}$$

$$\widetilde{\lambda}_h = \frac{1}{p^c}\left(C - \frac{\chi(L)^{1+1/f}}{1+1/f}\right)^{-1/\psi}, \tag{D.12}$$

$$\mathbb{M}^{\$} = \beta/\bar{\Pi}, \tag{D.13}$$

$$\mathbb{M} = \beta, \tag{D.14}$$

$$r^d = \mathbb{M}^{-1} = \beta^{-1}, \tag{D.15}$$

$$\Pi^c = \bar{\Pi}. \tag{D.16}$$

D.2 Final and intermediate goods firms

At steady state, the final goods firms' equilibrium system dictates by using Equations (33), (34), (35), (45), (58), (59), (61), (B.18), (B.19), (B.20), (B.21), (B.22), (B.23), (B.24), (B.26), (B.27), (B.28), and (B.29):

$$\Pi = \bar{\Pi}, \tag{D.17}$$

and for all $s = 1, \ldots, S$ also the following equations have to hold:

$$p_{s,t}^* = (f_{1,s} + f_{3,s})/f_{2,s}, \tag{D.18}$$

$$f_{1,s} = \frac{\mu \mathrm{mc}_s \left(\frac{Y_s}{\omega_{ys} Y}\right)^{-\theta} Y_s}{1 - \kappa_s \beta (\bar{\Pi})^{\theta}}, \tag{D.19}$$

$$f_{2,s} = \frac{\left(\frac{Y_s}{\omega_{ys} Y}\right)^{-\theta} Y_s}{1 - \kappa_s \beta (\bar{\Pi})^{\theta-1}}, \tag{D.20}$$

$$f_{3,s} = \frac{\mu \left(\frac{Y_s}{\omega_{ys} Y}\right)^{-\theta} [p_s \iota_{2s} (\psi_s^A)^{\iota_{3s}} + \tau_s^F \nu_s (1 - \psi_s^A)] Y_s}{1 - \kappa_s \beta (\bar{\Pi})^{\theta}}, \tag{D.21}$$

$$\mathrm{VA}_s = \left(\alpha_s (K_s)^{(\gamma_s - 1)/\gamma_s} + (1 - \alpha_s)(L_s)^{(\gamma_s - 1)/\gamma_s}\right)^{\gamma_s/(\gamma_s - 1)}, \tag{D.22}$$

$$\mathring{Y}_s = Y_s / \mathring{P}_s, \tag{D.23}$$

$$Y_s = (1 + K_g^p)^{\alpha_{gs}} A_s \left(\zeta_s (\mathrm{VA}_s)^{(\sigma_s - 1)/\sigma_s} + (1 - \zeta_s)(Z_s)^{(\sigma_s - 1)/\sigma_s}\right)^{\sigma_s/(\sigma_s - 1)}, \tag{D.24}$$

$$\mathring{P}_s = \frac{(1 - \kappa_s)(p_s / p_s^*)^{\theta}}{1 - \kappa_s (\bar{\Pi})^{\theta}}, \tag{D.25}$$

$$u_s = \bar{u}_s, \tag{D.26}$$

$$p^s = \prod_{r=1}^{S} (p_r)^{\omega_{sr}}, \tag{D.27}$$

$$p_r = p^s \omega_{sr} Z_s / Z_s(r), \quad r = 1, \ldots, S, \tag{D.28}$$

$$w_s = \mathrm{mc}_s (Y_s)^{1/\sigma_s} (A_s (1 + K_g^p)^{\alpha_{gs}}))^{1 - \sigma_s} \zeta_s (\mathrm{VA}_s)^{1/\gamma_s - 1/\sigma_s} (1 - \alpha_s)(L_s^d)^{-1/\gamma_s}, \tag{D.29}$$

$$(1 + \bar{\tau}_s^z) p^s = \mathrm{mc}_s (Y_s)^{1/\sigma_s} (A_s (1 + K_g^p)^{\alpha_{gs}}))^{1 - \sigma_s} (1 - \zeta_s)(Z_s)^{-1/\gamma_s}, \tag{D.30}$$

$$r_s^k = \mathrm{mc}_s (Y_s)^{1/\sigma_s} (A_s (1 + K_g^p)^{\alpha_{gs}}))^{1 - \sigma_s} \zeta_s (\mathrm{VA}_s)^{1/\gamma_s - 1/\sigma_s} \alpha_s (u_s K_s)^{-1/\gamma_s} u_s, \tag{D.31}$$

$$p_s^* = \left(\frac{(p_s)^{1-\theta} (1 - \kappa_s (\bar{\Pi})^{\theta - 1})}{1 - \kappa_s}\right)^{1/(1-\theta)}, \tag{D.32}$$

$$\psi_s^A = \left(\frac{\tau_s^F}{p_s} \frac{\nu_s}{\iota_{2s} \iota_{3s}}\right)^{1/(\iota_{3s} - 1)}, \tag{D.33}$$

$$X_s^A = \iota_{2s} (\psi_s^A)^{\iota_{3s}} \mathring{Y}_s. \tag{D.34}$$

D.3 Capital producers

At steady state, the equilibrium equations for the capital producers imply via Equations (63), (64), (75), (76), (B.31), (B.32), (B.33), and (B.34):

$$I_s = \delta_s K_s, \quad s = 1, \dots, S, \tag{D.35}$$

$$\Lambda_s = \delta_s, \quad s = 1, \dots, S, \tag{D.36}$$

$$\Lambda'_s = 1, \quad s = 1, \dots, S, \tag{D.37}$$

$$v_s^k = \frac{r_s^k K_s - (1 + \bar{\tau}_s^i) p_s^i I_s + (1 - r_s^i) \ell_s}{1 - \beta}, \quad s = 1, \dots, S, \tag{D.38}$$

$$q_s = (1 + \mu_{s,t}^{\mathtt{LIA}} \chi_s)(1 + \bar{\tau}_s^i) p_s^i, \quad s = 1, \dots, S, \tag{D.39}$$

$$q_s = \frac{\beta}{1 - \beta + \beta \delta_s} r_s^k, \quad s = 1, \dots, S, \tag{D.40}$$

$$\ell_s^i = \chi_s (1 + \bar{\tau}_s^i) p_s^i I_s, \quad s = 1, \dots, S, \tag{D.41}$$

$$1 + \mu_s^{\mathtt{LIA}} = \beta r_s^i, \quad s = 1, \dots, S. \tag{D.42}$$

D.4 Investment goods producers

At steady state, the equilibrium equations for the investment goods producers imply via Equations (B.35) and (B.36) for all $s = 1, \dots, S$:

$$p_s^i = \prod_{r=1}^{S} (p_r)^{\omega_{sr}^i}, \tag{D.43}$$

$$p_r = p_s^i \omega_{sr}^i I_s / I_s(r), \quad r = 1, \dots, S. \tag{D.44}$$

D.5 Banking sector

Equations (81), (82), (83), (84), (85), (89), (B.5), (B.48), (B.49), (B.50), (B.51) imply the following relations in the steady state for the banking sector:

$$r^d = R^d / \bar{\Pi}, \tag{D.45}$$

$$(1 - \mu^{\mathtt{icc}}) v = \Omega, \tag{D.46}$$

$$\Omega = 1 - \theta + \theta \cdot v, \tag{D.47}$$

$$\Phi = \varphi \cdot \mathrm{nw}, \tag{D.48}$$

$$\mathrm{nw} = \Delta_{bb} b_b^p + \Delta_{bg} b_g^p + \sum_{s=1}^{S} \bar{\Delta}_s \ell_s^{i,p}, \tag{D.49}$$

$$\mathrm{nw} + d = \mathrm{re} + b_b^p + b_g^p + \sum_{s=1}^{S} \ell_s^{i,p}, \tag{D.50}$$

$$(1 - r^d - \varphi)\text{nw} = \theta\left((r - r^d)\text{re} + (r_b^b - r^d)b_b^p + (r_g^b - r^d)b_g^p + \sum_{s=1}^{S}(r_s^i - r^d)\ell_s^{i,p}\right), \quad \text{(D.51)}$$

$$\mu^{\mathtt{icc}}\bar{\Delta}_s = \beta\Omega(r_s^i - r^d), \quad s = 1, \ldots, S, \quad \text{(D.52)}$$

$$\mu^{\mathtt{icc}}\Delta_{bb} = \beta\Omega(r_b^b - r^d), \quad \text{(D.53)}$$

$$\mu^{\mathtt{icc}}\Delta_{bg} = \beta\Omega(r_g^b - r^d), \quad \text{(D.54)}$$

$$\Delta_s = \bar{\Delta}_s, \quad s = 1, \ldots, S. \quad \text{(D.55)}$$

D.6 Public sector

Equations (90), (91), (92), (100), (102), (108), (109), (110), (113), (B.37), (B.38), (B.39), (B.40), (B.41), (B.42), (B.43), (B.44), (B.45), (B.46), (B.47), (B.58), (B.59), and (B.60) imply at the steady state for the public sector:

$$i = \bar{i}, \quad \text{(D.56)}$$

$$r = \bar{i}/\bar{\Pi}, \quad \text{(D.57)}$$

$$R^d = \bar{i}, \quad \text{(D.58)}$$

$$\tau_s^c = \bar{\tau}_s^c, \quad s = 1, \ldots, S, \quad \text{(D.59)}$$

$$\tau_s^z = \bar{\tau}_s^z, \quad s = 1, \ldots, S, \quad \text{(D.60)}$$

$$\tau_s^i = \bar{\tau}_s^i, \quad s = 1, \ldots, S, \quad \text{(D.61)}$$

$$\tau_s^F = \bar{\tau}_s^F, \quad s = 1, \ldots, S, \quad \text{(D.62)}$$

$$t = \sum_{s=1}^{S}[\tau_s^F \nu_s(1 - \psi_s^A)\mathring{Y}_s], \quad \text{(D.63)}$$

$$r_b^b b_b + r_g^b b_g + \sum_{s=1}^{S} G_s = b_b + b_g + t_{cb} + \tau^W \sum_{s=1}^{S} w_s L_s^d + \sum_{s=1}^{S}[\tau_s^c p_s C_s + \tau_s^z p^s Z_s + \tau_s^i p_s^i I_s], \quad \text{(D.64)}$$

$$b_b = b_b^p + b_b^{cb}, \quad \text{(D.65)}$$

$$B_g = B_g^p + B_g^{cb}, \quad \text{(D.66)}$$

$$\ell_s^i = \ell_s^{i,p} + \ell_s^{i,cb}, \quad s = 1, \ldots, S, \quad \text{(D.67)}$$

$$b_b^{cb} = \bar{s}_b^{cb} b_b, \quad \text{(D.68)}$$

$$b_g^{cb} = \bar{s}_g^{cb} b_g, \quad \text{(D.69)}$$

$$b_b = 0, \quad \text{(D.70)}$$

$$b_g = 0, \quad \text{(D.71)}$$

$$\ell_s^{i,cb} = \bar{s}_{\ell,s}^{cb} \ell_s^i, \quad s = 1, \ldots, S, \quad \text{(D.72)}$$

$$t_{cb} = r_b^b b_b^{cb} + r_g^b b_g^{cb} + \sum_{s=1}^{S}(r_s^i \ell_s^{i,cb}) - r \cdot \text{re}, \quad \text{(D.73)}$$

$$\text{re} = b_b^{cb} + b_g^{cb} + \sum_{s=1}^{S} \ell_s^{i,cb}, \tag{D.74}$$

$$p_s G_s = p^g \omega_{gs} G, \tag{D.75}$$

$$p^g G = \bar{g} Y, \tag{D.76}$$

$$p^g = \prod_{s=1}^{S} p_s^{\omega_{gs}}, \tag{D.77}$$

$$K_g^p = b_g / \delta_p. \tag{D.78}$$

D.7 Environment

Equations (25), (111), and (112) determine the steady state for the environment as follows:

$$\mathcal{E} = \sum_{s=1}^{S} \nu_s (1 - \psi_s^A) \mathring{Y}_s, \tag{D.79}$$

$$M = \mathcal{E} / \delta_m, \tag{D.80}$$

$$\Omega_s = e^{-\iota_{1s} \cdot M}. \tag{D.81}$$

D.8 Aggregate economy

Finally, aggregation in our closed economy framework implies the following conditions at the steady state via Equations (36), (B.56), and (B.57):

$$A_s = e^{\bar{a}}, \quad s = 1, \ldots, S, \tag{D.82}$$

$$\mathring{Y}_s = G_s + C_s + X_s^A + \sum_{r=1}^{S} I_r(s) + \sum_{r=1}^{S} Z_r(s), \quad s = 1, \ldots, S, \tag{D.83}$$

$$Y = \sum_{s=1}^{S} p_s \mathring{Y}_s. \tag{D.84}$$

E Data Summary and Parameters for Multi-Sector Model

Table E.1: NACE level 1 and 2 sectors

Code	Description
A	Agriculture, forestry and fishing
B	Mining and quarrying
C10–C12	Manufacture of food products, beverages and tobacco products
C13–C15	Manufacture of textiles, wearing apparel and leather products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31–C32	Manufacture of furniture; other manufacturing
C33	Repair and installation of machinery and equipment
D	Electricity, gas, steam and air conditioning supply
E	Water supply; sewerage; waste managment and remediation activities
F	Construction
G	Wholesale and retail trade; repair of motor vehicles and motorcycles
H	Transporting and storage
I	Accommodation and food service activities
J	Information and communication
K	Financial and insurance activities
L	Real estate activities
M	Professional, scientific and technical activities
N	Administrative and support service activities
O	Public administration and defence; compulsory social security
P	Education
Q	Human health and social work activities
R–S	Arts, entertainment and recreation; other services activities
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
U	Activities of extraterritorial organisations and bodies

Notes: This table reports the codes and descriptions of the NACE level 1 and 2 sectors, represented in our calibrated model.

Table E.2: Values of sector-specific parameters

Code	type of sector	ω_{cs}	ω_{gs}	ω_{ys}	ζ_s	α_s	ν_s	ι_{1s}	α_{gs}
A	brown	0.0192	0.0006	0.0201	0.4959	0.7355	974.15	$1 \cdot 10^{-8}$	0
B	brown	0.0006	0.0000	0.0024	0.5562	0.6664	383.54	$1 \cdot 10^{-8}$	0
C10–C12	brown	0.0795	0.0007	0.0385	0.2601	0.4966	68.63	$1 \cdot 10^{-8}$	0
C13–C15	brown	0.0099	0.0001	0.0051	0.2661	0.4164	58.99	$1 \cdot 10^{-8}$	0
C16	brown	0.0013	0.0001	0.0045	0.3000	0.4474	40.23	$1 \cdot 10^{-8}$	0
C17	brown	0.0034	0.0001	0.0054	0.2874	0.4840	275.83	$1 \cdot 10^{-8}$	0
C18	brown	0.0008	0.0000	0.0026	0.3911	0.3584	42.08	$1 \cdot 10^{-8}$	0
C19	brown	0.0130	0.0001	0.0093	0.1984	0.7649	618.81	$1 \cdot 10^{-8}$	0
C20	brown	0.0066	0.0013	0.0149	0.2879	0.5997	449.81	$1 \cdot 10^{-8}$	0
C21	brown	0.0065	0.0127	0.0054	0.4303	0.7050	36.64	$1 \cdot 10^{-8}$	0
C22	brown	0.0033	0.0002	0.0089	0.2750	0.3859	39.81	$1 \cdot 10^{-8}$	0
C23	brown	0.0024	0.0001	0.0074	0.3363	0.4412	1046.51	$1 \cdot 10^{-8}$	0
C24	brown	0.0007	0.0001	0.0112	0.2145	0.4086	620.08	$1 \cdot 10^{-8}$	0
C25	brown	0.0032	0.0002	0.0174	0.3298	0.3550	24.80	$1 \cdot 10^{-8}$	0
C26	brown	0.0039	0.0008	0.0063	0.3106	0.5624	20.89	$1 \cdot 10^{-8}$	0
C27	brown	0.0041	0.0003	0.0077	0.2654	0.3585	19.60	$1 \cdot 10^{-8}$	0
C28	brown	0.0027	0.0006	0.0183	0.3112	0.3708	25.64	$1 \cdot 10^{-8}$	0
C29	brown	0.0258	0.0011	0.0247	0.2401	0.4880	20.40	$1 \cdot 10^{-8}$	0
C30	brown	0.0021	0.0005	0.0058	0.3346	0.4457	14.55	$1 \cdot 10^{-8}$	0
C31–C32	brown	0.0098	0.0024	0.0069	0.3679	0.3835	18.16	$1 \cdot 10^{-8}$	0
C33	brown	0.0006	0.0001	0.0081	0.4734	0.2734	14.32	$1 \cdot 10^{-8}$	0
D	brown	0.0301	0.0006	0.0314	0.3937	0.7557	827.94	$1 \cdot 10^{-8}$	0
E	brown	0.0113	0.0051	0.0128	0.5032	0.5349	505.71	$1 \cdot 10^{-8}$	0
F	brown	0.0100	0.0018	0.0772	0.3787	0.4642	28.02	$1 \cdot 10^{-8}$	0
G	green	0.1771	0.0191	0.1043	0.5783	0.4567	31.42	$1 \cdot 10^{-8}$	0.05
H	brown	0.0365	0.0174	0.0547	0.4728	0.4451	265.37	$1 \cdot 10^{-8}$	0
I	green	0.0708	0.0009	0.0224	0.4880	0.4072	32.42	$1 \cdot 10^{-8}$	0.05
J	brown	0.0308	0.0103	0.0496	0.5477	0.5098	4.12	$1 \cdot 10^{-8}$	0
K	green	0.0554	0.0007	0.0524	0.5926	0.5461	4.25	$1 \cdot 10^{-8}$	0.05
L	brown	0.2043	0.0094	0.0780	0.7552	0.9503	1305.98	$1 \cdot 10^{-8}$	0
M	green	0.0100	0.0148	0.0691	0.5403	0.3772	9.28	$1 \cdot 10^{-8}$	0.05
N	green	0.0143	0.0021	0.0389	0.5681	0.3968	20.24	$1 \cdot 10^{-8}$	0.05
O	green	0.0083	0.3482	0.0545	0.6543	0.3336	20.16	$1 \cdot 10^{-8}$	0.05
P	green	0.0167	0.1796	0.0328	0.7636	0.2339	14.71	$1 \cdot 10^{-8}$	0.05
Q	green	0.0607	0.3411	0.0647	0.6277	0.2764	29.26	$1 \cdot 10^{-8}$	0.05
R–S	green	0.0566	0.0263	0.0244	0.5854	0.4134	29.87	$1 \cdot 10^{-8}$	0.05
T	green	0.0076	0.0006	0.0020	0.3879	0.3629	3.65	$1 \cdot 10^{-8}$	0.05

Notes: This table reports the first part of the calculated parameters for the 37-sector model.

Table E.3: Values for ω_{sr}

Code	A	B	C10-C12	C13–C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31–C32	C33	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R–S	T
A	0.2810	0.0024	0.1637	0.0026	0.0052	0.0026	0.0004	0.0333	0.0527	0.0061	0.0077	0.0064	0.0014	0.0085	0.0015	0.0027	0.0129	0.0044	0.0019	0.0024	0.0245	0.0319	0.0156	0.0199	0.1427	0.0239	0.0018	0.0068	0.0356	0.0083	0.0373	0.0389	0.0060	0.0013	0.0010	0.0044	0.0001
B	0.0037	0.0951	0.0078	0.0011	0.0087	0.0061	0.0012	0.0248	0.0266	0.0016	0.0060	0.0193	0.0096	0.0195	0.0024	0.0051	0.0264	0.0042	0.0031	0.0019	0.0361	0.1039	0.0377	0.0354	0.1042	0.1049	0.0076	0.0397	0.0366	0.0190	0.0940	0.0709	0.0228	0.0038	0.0024	0.0068	0.0000
C10-C12	0.2779	0.0015	0.2647	0.0010	0.0031	0.0170	0.0015	0.0023	0.0107	0.0025	0.0138	0.0058	0.0016	0.0083	0.0009	0.0019	0.0058	0.0016	0.0006	0.0015	0.0041	0.0221	0.0108	0.0073	0.1218	0.0633	0.0025	0.0121	0.0192	0.0113	0.0543	0.0332	0.0055	0.0022	0.0011	0.0051	0.0001
C13–C15	0.0237	0.0010	0.0210	0.3093	0.0020	0.0085	0.0025	0.0034	0.0558	0.0025	0.0234	0.0036	0.0030	0.0094	0.0014	0.0032	0.0105	0.0024	0.0014	0.0056	0.0070	0.0266	0.0166	0.0137	0.1719	0.0508	0.0055	0.0184	0.0331	0.0286	0.0672	0.0450	0.0079	0.0026	0.0013	0.0102	0.0000
C16	0.1459	0.0006	0.0031	0.0058	0.2822	0.0108	0.0013	0.0037	0.0402	0.0025	0.0139	0.0161	0.0040	0.0165	0.0016	0.0027	0.0076	0.0024	0.0009	0.0094	0.0106	0.0341	0.0164	0.0164	0.1402	0.0722	0.0032	0.0114	0.0227	0.0178	0.0362	0.0331	0.0091	0.0012	0.0009	0.0029	0.0000
C17	0.0359	0.0033	0.0090	0.0100	0.0222	0.2829	0.0139	0.0041	0.0515	0.0022	0.0197	0.0019	0.0042	0.0085	0.0023	0.0034	0.0114	0.0019	0.0010	0.0031	0.0151	0.0706	0.0541	0.0111	0.1038	0.0885	0.0039	0.0194	0.0221	0.0129	0.0488	0.0367	0.0115	0.0018	0.0009	0.0062	0.0000
C18	0.0012	0.0010	0.0040	0.0071	0.0031	0.1994	0.1056	0.0032	0.0488	0.0029	0.0200	0.0016	0.0044	0.0086	0.0078	0.0041	0.0126	0.0039	0.0014	0.0031	0.0099	0.0336	0.0098	0.0255	0.1173	0.0545	0.0044	0.0429	0.0333	0.0356	0.0752	0.0812	0.0120	0.0053	0.0017	0.0140	0.0000
C19	0.0012	0.0964	0.0075	0.0008	0.0007	0.0013	0.0004	0.2045	0.0773	0.0024	0.0101	0.0139	0.0050	0.0084	0.0015	0.0032	0.0071	0.0026	0.0008	0.0014	0.0058	0.0404	0.0109	0.0138	0.1548	0.1292	0.0146	0.0130	0.0287	0.0048	0.0698	0.0305	0.0174	0.0020	0.0018	0.0157	0.0000
C20	0.0062	0.0078	0.0280	0.0022	0.0026	0.0114	0.0021	0.0637	0.3253	0.0148	0.0197	0.0074	0.0140	0.0112	0.0021	0.0031	0.0078	0.0035	0.0007	0.0036	0.0093	0.0554	0.0184	0.0127	0.1173	0.0657	0.0032	0.0216	0.0259	0.0105	0.0665	0.0385	0.0088	0.0033	0.0009	0.0046	0.0000
C21	0.0028	0.0013	0.0265	0.0032	0.0027	0.0190	0.0052	0.0053	0.1149	0.1414	0.0215	0.0090	0.0061	0.0068	0.0052	0.0029	0.0106	0.0037	0.0010	0.0054	0.0037	0.0211	0.0101	0.0179	0.1594	0.0462	0.0060	0.0347	0.0284	0.0156	0.1344	0.0935	0.0105	0.0094	0.0026	0.0119	0.0000
C22	0.0100	0.0011	0.0054	0.0089	0.0041	0.0142	0.0025	0.0079	0.2348	0.0086	0.1615	0.0091	0.0151	0.0253	0.0021	0.0048	0.0139	0.0055	0.0019	0.0049	0.0062	0.0431	0.0356	0.0119	0.1104	0.0651	0.0023	0.0187	0.0253	0.0203	0.0594	0.0449	0.0088	0.0027	0.0009	0.0030	0.0000
C23	0.0011	0.0598	0.0045	0.0020	0.0077	0.0090	0.0014	0.0143	0.0363	0.0025	0.0174	0.1928	0.0194	0.0160	0.0025	0.0046	0.0122	0.0072	0.0012	0.0026	0.0122	0.0873	0.0238	0.0227	0.1324	0.1035	0.0030	0.0200	0.0264	0.0188	0.0652	0.0520	0.0101	0.0024	0.0009	0.0045	0.0000
C24	0.0010	0.0122	0.0040	0.0010	0.0030	0.0033	0.0009	0.0128	0.0272	0.0014	0.0074	0.0094	0.3371	0.0507	0.0024	0.0067	0.0183	0.0027	0.0014	0.0029	0.0198	0.0824	0.0964	0.0159	0.0849	0.0622	0.0044	0.0132	0.0168	0.0083	0.0384	0.0311	0.0133	0.0015	0.0010	0.0045	0.0000
C25	0.0007	0.0015	0.0021	0.0019	0.0045	0.0045	0.0015	0.0027	0.0187	0.0013	0.0223	0.0101	0.1846	0.2839	0.0042	0.0121	0.0328	0.0101	0.0033	0.0043	0.0166	0.0293	0.0237	0.0131	0.0984	0.0374	0.0031	0.0203	0.0230	0.0218	0.0477	0.0457	0.0068	0.0027	0.0007	0.0026	0.0000
C26	0.0014	0.0007	0.0037	0.0024	0.0031	0.0082	0.0024	0.0023	0.0228	0.0041	0.0220	0.0121	0.0325	0.0428	0.1237	0.0446	0.0320	0.0218	0.0024	0.0126	0.0150	0.0205	0.0061	0.0126	0.2153	0.0663	0.0029	0.0479	0.0264	0.0182	0.0916	0.0571	0.0083	0.0075	0.0013	0.0052	0.0000
C27	0.0007	0.0009	0.0026	0.0019	0.0032	0.0092	0.0021	0.0033	0.0231	0.0028	0.0408	0.0120	0.0962	0.0701	0.0304	0.1630	0.0335	0.0163	0.0027	0.0031	0.0136	0.0259	0.0065	0.0130	0.1434	0.0607	0.0026	0.0283	0.0239	0.0194	0.0813	0.0459	0.0082	0.0044	0.0009	0.0038	0.0000
C28	0.0006	0.0007	0.0021	0.0015	0.0029	0.0038	0.0014	0.0027	0.0093	0.0012	0.0305	0.0042	0.0618	0.1358	0.0094	0.0254	0.2292	0.0420	0.0049	0.0074	0.0193	0.0127	0.0062	0.0167	0.1212	0.0506	0.0060	0.0242	0.0226	0.0176	0.0688	0.0441	0.0051	0.0031	0.0011	0.0036	0.0000
C29	0.0006	0.0004	0.0018	0.0050	0.0027	0.0020	0.0014	0.0018	0.0139	0.0012	0.0465	0.0079	0.0572	0.0734	0.0085	0.0203	0.0516	0.2969	0.0072	0.0052	0.0158	0.0127	0.0068	0.0118	0.1530	0.0439	0.0014	0.0168	0.0164	0.0142	0.0561	0.0321	0.0045	0.0049	0.0008	0.0034	0.0000
C30	0.0006	0.0007	0.0018	0.0042	0.0088	0.0025	0.0010	0.0016	0.0152	0.0012	0.0234	0.0061	0.0322	0.0854	0.0237	0.0232	0.0609	0.0197	0.2396	0.0050	0.0631	0.0099	0.0076	0.0136	0.1319	0.0261	0.0039	0.0204	0.0225	0.0120	0.0672	0.0485	0.0045	0.0055	0.0015	0.0048	0.0000
C31–C32	0.0034	0.0014	0.0055	0.0184	0.0968	0.0122	0.0038	0.0047	0.0334	0.0029	0.0341	0.0129	0.0322	0.0454	0.0170	0.0142	0.0160	0.0091	0.0051	0.1015	0.0093	0.0166	0.0090	0.0156	0.2033	0.0598	0.0042	0.0223	0.0285	0.0263	0.0688	0.0455	0.0065	0.0027	0.0022	0.0092	0.0000
C33	0.0006	0.0009	0.0033	0.0032	0.0030	0.0033	0.0011	0.0031	0.0149	0.0014	0.0270	0.0075	0.0585	0.1120	0.0235	0.0296	0.0838	0.0205	0.0381	0.0087	0.1194	0.0115	0.0077	0.0227	0.1429	0.0336	0.0073	0.0211	0.0200	0.0171	0.0648	0.0663	0.0055	0.0068	0.0020	0.0072	0.0000
D	0.0045	0.0148	0.0026	0.0004	0.0038	0.0019	0.0006	0.0173	0.0171	0.0010	0.0031	0.0063	0.0032	0.0078	0.0051	0.0123	0.0092	0.0022	0.0008	0.0010	0.0098	0.5631	0.0099	0.0374	0.0425	0.0434	0.0035	0.0191	0.0284	0.0135	0.0408	0.0323	0.0331	0.0032	0.0008	0.0041	0.0000
E	0.0012	0.0025	0.0062	0.0015	0.0036	0.0085	0.0018	0.0075	0.0139	0.0017	0.0070	0.0067	0.0176	0.0242	0.0019	0.0045	0.0134	0.0106	0.0014	0.0017	0.0105	0.0411	0.3080	0.0569	0.0761	0.0472	0.0047	0.0327	0.0322	0.0189	0.0793	0.0937	0.0442	0.0031	0.0036	0.0105	0.0000
F	0.0022	0.0092	0.0026	0.0020	0.0259	0.0019	0.0006	0.0079	0.0136	0.0015	0.0312	0.0793	0.0178	0.0565	0.0039	0.0215	0.0199	0.0071	0.0018	0.0056	0.0079	0.0098	0.0093	0.3062	0.0910	0.0246	0.0077	0.0113	0.0280	0.0420	0.0730	0.0587	0.0109	0.0020	0.0011	0.0045	0.0000
G	0.0052	0.0008	0.0102	0.0027	0.0019	0.0064	0.0053	0.0071	0.0066	0.0015	0.0102	0.0032	0.0026	0.0059	0.0029	0.0040	0.0074	0.0192	0.0018	0.0023	0.0061	0.0290	0.0091	0.0179	0.1386	0.2009	0.0126	0.0486	0.0607	0.1169	0.1338	0.0897	0.0090	0.0060	0.0035	0.0105	0.0000
H	0.0011	0.0010	0.0054	0.0007	0.0011	0.0027	0.0022	0.0416	0.0036	0.0008	0.0051	0.0015	0.0023	0.0054	0.0020	0.0031	0.0063	0.0112	0.0043	0.0015	0.0117	0.0251	0.0049	0.0262	0.0733	0.4738	0.0123	0.0331	0.0446	0.0296	0.0607	0.0753	0.0124	0.0062	0.0016	0.0060	0.0000
I	0.0479	0.0010	0.3215	0.0030	0.0019	0.0057	0.0027	0.0037	0.0075	0.0018	0.0032	0.0036	0.0010	0.0033	0.0012	0.0041	0.0041	0.0014	0.0012	0.0032	0.0025	0.0378	0.0198	0.0186	0.1584	0.0292	0.0131	0.0332	0.0350	0.0982	0.0509	0.0483	0.0081	0.0023	0.0038	0.0182	0.0000
J	0.0007	0.0004	0.0044	0.0014	0.0014	0.0092	0.0180	0.0021	0.0046	0.0014	0.0039	0.0012	0.0012	0.0035	0.0145	0.0062	0.0067	0.0056	0.0016	0.0022	0.0047	0.0183	0.0058	0.0176	0.0853	0.0352	0.0092	0.4067	0.0357	0.0492	0.1211	0.0816	0.0090	0.0097	0.0027	0.0183	0.0000
K	0.0002	0.0001	0.0011	0.0003	0.0002	0.0029	0.0050	0.0013	0.0012	0.0006	0.0010	0.0002	0.0003	0.0005	0.0017	0.0007	0.0012	0.0012	0.0002	0.0008	0.0007	0.0070	0.0026	0.0106	0.0216	0.0178	0.0061	0.0781	0.5824	0.0501	0.1233	0.0584	0.0056	0.0056	0.0019	0.0072	0.0000
L	0.0008	0.0010	0.0023	0.0009	0.0044	0.0020	0.0016	0.0016	0.0050	0.0009	0.0032	0.0072	0.0027	0.0057	0.0012	0.0025	0.0025	0.0011	0.0004	0.0017	0.0029	0.0214	0.0159	0.2538	0.0194	0.0087	0.0045	0.0174	0.2795	0.1313	0.1128	0.0625	0.0129	0.0032	0.0009	0.0041	0.0000
M	0.0010	0.0007	0.0060	0.0013	0.0011	0.0083	0.0108	0.0036	0.0065	0.0030	0.0052	0.0022	0.0024	0.0045	0.0056	0.0043	0.0064	0.0035	0.0012	0.0026	0.0036	0.0137	0.0070	0.0229	0.0497	0.0308	0.0109	0.1010	0.0541	0.0666	0.4195	0.0896	0.0197	0.0115	0.0049	0.0141	0.0000
N	0.0086	0.0010	0.0072	0.0031	0.0042	0.0128	0.0136	0.0068	0.0108	0.0028	0.0099	0.0052	0.0023	0.0097	0.0048	0.0053	0.0085	0.0079	0.0053	0.0035	0.0061	0.0119	0.0110	0.0253	0.0745	0.0584	0.0269	0.0681	0.0539	0.0685	0.1882	0.2243	0.0143	0.0073	0.0089	0.0191	0.0000
O	0.0048	0.0022	0.0210	0.0019	0.0014	0.0049	0.0074	0.0083	0.0054	0.0017	0.0022	0.0025	0.0026	0.0069	0.0054	0.0031	0.0049	0.0043	0.0159	0.0033	0.0112	0.0402	0.0551	0.0839	0.0578	0.0696	0.0105	0.0833	0.0755	0.0617	0.1024	0.1229	0.0488	0.0255	0.0117	0.0298	0.0001
P	0.0039	0.0008	0.0362	0.0017	0.0023	0.0061	0.0096	0.0071	0.0055	0.0032	0.0017	0.0028	0.0008	0.0027	0.0041	0.0021	0.0029	0.0026	0.0010	0.0051	0.0029	0.0523	0.0173	0.0734	0.0622	0.0908	0.0240	0.0788	0.0470	0.0465	0.0792	0.1080	0.0121	0.1645	0.0141	0.0248	0.0000
Q	0.0044	0.0006	0.0486	0.0042	0.0014	0.0045	0.0032	0.0045	0.0217	0.0599	0.0064	0.0035	0.0043	0.0037	0.0077	0.0028	0.0052	0.0026	0.0011	0.0342	0.0081	0.0358	0.0151	0.0355	0.1514	0.0251	0.0181	0.0422	0.0384	0.0516	0.0593	0.0831	0.0099	0.0161	0.1667	0.0188	0.0000
R–S	0.0048	0.0008	0.0184	0.0053	0.0081	0.0053	0.0119	0.0063	0.0137	0.0033	0.0061	0.0036	0.0023	0.0054	0.0054	0.0047	0.0058	0.0039	0.0017	0.0071	0.0051	0.0479	0.0165	0.0323	0.0778	0.0432	0.0238	0.0883	0.0582	0.0621	0.1124	0.0906	0.0182	0.0103	0.0077	0.1816	0.0000
T	0.0221	0.0001	0.0013	0.0003	0.0016	0.0106	0.0001	0.0004	0.0120	0.0004	0.0215	0.0003	0.0012	0.0022	0.0022	0.0283	0.0078	0.0014	0.0002	0.0007	0.0004	0.2602	0.0762	0.0161	0.4016	0.0027	0.0001	0.0023	0.0054	0.0825	0.0008	0.0267	0.0016	0.0001	0.0012	0.0064	0.0007

Notes: This table reports the second part of the calculated parameters for the 37-sector model.

Table E.4: Values for ω^i_{sr}

Code	A	B	C10-C12	C13–C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31–C32	C33	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R–S	T
A	0.0492	0.0003	0.0001	0.0002	0.0003	0.0000	0.0001	0.0000	0.0005	0.0000	0.0005	0.0003	0.0004	0.0729	0.0335	0.0835	0.1076	0.0252	0.0177	0.0196	0.1241	0.0064	0.0011	0.3265	0.0035	0.0050	0.0003	0.0060	0.0025	0.0190	0.0026	0.0040	0.0009	0.0024	0.0001	0.0838	0.0000
B	0.0001	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001	0.0000	0.0006	0.0000	0.0004	0.0002	0.0004	0.0884	0.0436	0.1036	0.1306	0.0252	0.0122	0.0233	0.1443	0.0026	0.0006	0.1365	0.0036	0.0026	0.0002	0.0361	0.0327	0.0082	0.0328	0.0334	0.0004	0.0326	0.0001	0.1039	0.0000
C10-C12	0.0003	0.0001	0.0001	0.0002	0.0003	0.0000	0.0001	0.0000	0.0004	0.0000	0.0005	0.0002	0.0004	0.1103	0.0516	0.1286	0.1590	0.0302	0.0148	0.0284	0.1767	0.0029	0.0005	0.1369	0.0030	0.0024	0.0001	0.0076	0.0015	0.0079	0.0021	0.0022	0.0004	0.0015	0.0001	0.1287	0.0000
C13–C15	0.0001	0.0002	0.0001	0.0002	0.0004	0.0000	0.0002	0.0000	0.0004	0.0000	0.0006	0.0003	0.0004	0.1019	0.0517	0.1205	0.1475	0.0276	0.0127	0.0261	0.1662	0.0033	0.0007	0.1660	0.0046	0.0033	0.0003	0.0151	0.0018	0.0101	0.0027	0.0029	0.0005	0.0019	0.0001	0.1296	0.0000
C16	0.0001	0.0001	0.0001	0.0002	0.0003	0.0000	0.0001	0.0000	0.0004	0.0000	0.0005	0.0003	0.0004	0.1112	0.0574	0.1319	0.1655	0.0309	0.0151	0.0273	0.1837	0.0024	0.0005	0.1126	0.0031	0.0024	0.0001	0.0079	0.0011	0.0058	0.0025	0.0019	0.0003	0.0012	0.0001	0.1324	0.0000
C17	0.0001	0.0001	0.0001	0.0002	0.0004	0.0000	0.0001	0.0000	0.0004	0.0000	0.0006	0.0002	0.0004	0.1131	0.0572	0.1345	0.1656	0.0304	0.0139	0.0269	0.1842	0.0023	0.0005	0.1068	0.0030	0.0021	0.0002	0.0083	0.0011	0.0065	0.0023	0.0018	0.0003	0.0011	0.0001	0.1353	0.0000
C18	0.0003	0.0003	0.0002	0.0001	0.0001	0.0001	0.0009	0.0002	0.0020	0.0001	0.0003	0.0003	0.0003	0.0274	0.0245	0.0397	0.0564	0.0133	0.0100	0.0075	0.0620	0.0055	0.0010	0.1410	0.0078	0.0056	0.0002	0.1531	0.0791	0.0069	0.0798	0.0799	0.0009	0.0787	0.0002	0.1141	0.0000
C19	0.0004	0.0002	0.0001	0.0002	0.0004	0.0000	0.0002	0.0000	0.0004	0.0000	0.0006	0.0003	0.0005	0.1043	0.0516	0.1231	0.1493	0.0276	0.0128	0.0275	0.1687	0.0019	0.0005	0.1638	0.0037	0.0025	0.0003	0.0081	0.0033	0.0114	0.0038	0.0041	0.0005	0.0032	0.0001	0.1244	0.0000
C20	0.0002	0.0001	0.0001	0.0002	0.0004	0.0001	0.0002	0.0000	0.0007	0.0000	0.0006	0.0002	0.0005	0.1112	0.0550	0.1314	0.1622	0.0316	0.0147	0.0293	0.1809	0.0029	0.0005	0.1047	0.0031	0.0024	0.0001	0.0132	0.0020	0.0055	0.0046	0.0026	0.0003	0.0022	0.0001	0.1363	0.0000
C21	0.0006	0.0001	0.0001	0.0002	0.0004	0.0000	0.0002	0.0000	0.0005	0.0001	0.0005	0.0002	0.0004	0.1071	0.0533	0.1276	0.1547	0.0289	0.0140	0.0283	0.1745	0.0015	0.0003	0.1285	0.0026	0.0018	0.0001	0.0163	0.0019	0.0080	0.0046	0.0023	0.0003	0.0021	0.0001	0.1379	0.0000
C22	0.0003	0.0001	0.0001	0.0002	0.0003	0.0000	0.0001	0.0000	0.0005	0.0000	0.0005	0.0002	0.0004	0.1133	0.0548	0.1339	0.1658	0.0322	0.0156	0.0291	0.1837	0.0026	0.0005	0.1056	0.0027	0.0022	0.0001	0.0081	0.0011	0.0062	0.0022	0.0016	0.0003	0.0012	0.0001	0.1343	0.0000
C23	0.0003	0.0002	0.0001	0.0002	0.0004	0.0000	0.0002	0.0000	0.0005	0.0000	0.0006	0.0003	0.0004	0.1101	0.0547	0.1303	0.1596	0.0307	0.0142	0.0288	0.1790	0.0026	0.0005	0.1256	0.0035	0.0024	0.0002	0.0077	0.0013	0.0078	0.0024	0.0020	0.0004	0.0014	0.0001	0.1315	0.0000
C24	0.0001	0.0002	0.0001	0.0002	0.0003	0.0000	0.0001	0.0000	0.0005	0.0000	0.0006	0.0003	0.0004	0.1122	0.0544	0.1323	0.1632	0.0321	0.0153	0.0287	0.1819	0.0027	0.0005	0.1157	0.0033	0.0027	0.0001	0.0065	0.0013	0.0064	0.0025	0.0019	0.0003	0.0014	0.0001	0.1314	0.0000
C25	0.0001	0.0001	0.0001	0.0002	0.0003	0.0001	0.0001	0.0000	0.0006	0.0000	0.0006	0.0002	0.0004	0.1090	0.0542	0.1293	0.1606	0.0316	0.0153	0.0280	0.1786	0.0031	0.0005	0.1171	0.0029	0.0026	0.0001	0.0137	0.0014	0.0062	0.0038	0.0021	0.0003	0.0016	0.0001	0.1353	0.0000
C26	0.0004	0.0001	0.0001	0.0002	0.0003	0.0001	0.0002	0.0000	0.0008	0.0000	0.0005	0.0002	0.0004	0.1006	0.0531	0.1210	0.1527	0.0298	0.0146	0.0261	0.1684	0.0030	0.0005	0.1141	0.0036	0.0028	0.0001	0.0370	0.0020	0.0060	0.0065	0.0026	0.0004	0.0023	0.0001	0.1495	0.0000
C27	0.0002	0.0001	0.0001	0.0002	0.0003	0.0001	0.0002	0.0000	0.0007	0.0000	0.0006	0.0002	0.0004	0.1035	0.0541	0.1243	0.1561	0.0306	0.0149	0.0267	0.1725	0.0034	0.0006	0.1145	0.0033	0.0027	0.0001	0.0274	0.0017	0.0058	0.0066	0.0024	0.0003	0.0022	0.0001	0.1433	0.0000
C28	0.0002	0.0001	0.0001	0.0002	0.0002	0.0001	0.0002	0.0000	0.0007	0.0000	0.0005	0.0002	0.0004	0.1053	0.0547	0.1265	0.1592	0.0314	0.0154	0.0273	0.1755	0.0032	0.0005	0.1016	0.0031	0.0025	0.0001	0.0283	0.0017	0.0052	0.0049	0.0023	0.0003	0.0020	0.0001	0.1459	0.0000
C29	0.0002	0.0001	0.0001	0.0001	0.0002	0.0001	0.0002	0.0000	0.0007	0.0000	0.0005	0.0002	0.0004	0.1075	0.0558	0.1293	0.1631	0.0324	0.0159	0.0281	0.1793	0.0029	0.0005	0.0860	0.0030	0.0024	0.0001	0.0282	0.0017	0.0045	0.0036	0.0022	0.0003	0.0019	0.0001	0.1483	0.0000
C30	0.0002	0.0001	0.0001	0.0001	0.0002	0.0001	0.0002	0.0000	0.0007	0.0000	0.0005	0.0002	0.0004	0.1100	0.0562	0.1319	0.1657	0.0330	0.0163	0.0287	0.1825	0.0027	0.0005	0.0793	0.0027	0.0022	0.0001	0.0251	0.0015	0.0043	0.0028	0.0020	0.0003	0.0017	0.0001	0.1479	0.0000
C31–C32	0.0003	0.0001	0.0001	0.0002	0.0003	0.0001	0.0002	0.0000	0.0006	0.0000	0.0005	0.0002	0.0004	0.0986	0.0509	0.1174	0.1479	0.0293	0.0149	0.0258	0.1644	0.0030	0.0005	0.1334	0.0033	0.0029	0.0001	0.0378	0.0019	0.0075	0.0044	0.0026	0.0004	0.0021	0.0001	0.1477	0.0000
C33	0.0002	0.0001	0.0001	0.0002	0.0003	0.0001	0.0002	0.0000	0.0007	0.0000	0.0005	0.0002	0.0004	0.1069	0.0546	0.1277	0.1600	0.0315	0.0154	0.0277	0.1769	0.0030	0.0005	0.1041	0.0030	0.0025	0.0001	0.0241	0.0016	0.0055	0.0042	0.0022	0.0003	0.0018	0.0001	0.1434	0.0000
D	0.0004	0.0003	0.0001	0.0002	0.0004	0.0001	0.0002	0.0000	0.0006	0.0000	0.0005	0.0003	0.0004	0.0723	0.0373	0.0859	0.1049	0.0208	0.0106	0.0190	0.1202	0.0091	0.0014	0.3744	0.0035	0.0059	0.0003	0.0102	0.0018	0.0200	0.0021	0.0038	0.0006	0.0017	0.0001	0.0906	0.0000
E	0.0002	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001	0.0000	0.0008	0.0000	0.0004	0.0002	0.0003	0.0683	0.0355	0.0816	0.1031	0.0203	0.0113	0.0176	0.1151	0.0136	0.0018	0.3950	0.0028	0.0072	0.0002	0.0107	0.0021	0.0181	0.0023	0.0040	0.0006	0.0020	0.0001	0.0838	0.0000
F	0.0004	0.0005	0.0002	0.0001	0.0002	0.0001	0.0001	0.0000	0.0005	0.0000	0.0004	0.0004	0.0003	0.0607	0.0314	0.0719	0.1126	0.0400	0.0367	0.0155	0.1287	0.0050	0.0011	0.3525	0.0043	0.0042	0.0004	0.0132	0.0017	0.0263	0.0020	0.0031	0.0011	0.0016	0.0001	0.0824	0.0000
G	0.0003	0.0002	0.0001	0.0002	0.0002	0.0001	0.0002	0.0000	0.0007	0.0000	0.0005	0.0003	0.0003	0.0609	0.0410	0.0754	0.1221	0.0402	0.0370	0.0158	0.1390	0.0061	0.0010	0.2893	0.0050	0.0054	0.0003	0.0277	0.0031	0.0179	0.0040	0.0047	0.0009	0.0030	0.0001	0.0968	0.0000
H	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0002	0.0000	0.0005	0.0000	0.0003	0.0002	0.0003	0.0347	0.0422	0.0621	0.1421	0.0767	0.0883	0.0093	0.1653	0.0059	0.0009	0.2425	0.0037	0.0044	0.0002	0.0162	0.0043	0.0133	0.0046	0.0055	0.0005	0.0042	0.0001	0.0707	0.0000
I	0.0004	0.0006	0.0002	0.0003	0.0005	0.0001	0.0003	0.0000	0.0006	0.0000	0.0006	0.0005	0.0005	0.0595	0.0392	0.0753	0.0941	0.0209	0.0124	0.0176	0.1111	0.0058	0.0013	0.4093	0.0070	0.0060	0.0005	0.0107	0.0025	0.0284	0.0027	0.0043	0.0012	0.0024	0.0001	0.0834	0.0000
J	0.0004	0.0002	0.0001	0.0001	0.0001	0.0000	0.0003	0.0000	0.0006	0.0000	0.0003	0.0002	0.0003	0.0398	0.0549	0.0743	0.1338	0.0522	0.0554	0.0108	0.1501	0.0048	0.0008	0.2066	0.0047	0.0045	0.0002	0.0445	0.0098	0.0120	0.0110	0.0109	0.0007	0.0098	0.0001	0.1055	0.0000
K	0.0005	0.0002	0.0002	0.0001	0.0002	0.0001	0.0002	0.0000	0.0005	0.0000	0.0003	0.0003	0.0003	0.0350	0.0359	0.0487	0.1076	0.0490	0.0524	0.0100	0.1233	0.0061	0.0010	0.3404	0.0049	0.0065	0.0003	0.0464	0.0044	0.0199	0.0059	0.0059	0.0014	0.0041	0.0001	0.0879	0.0000
L	0.0004	0.0005	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0009	0.0000	0.0003	0.0004	0.0002	0.0032	0.0026	0.0034	0.0058	0.0021	0.0019	0.0014	0.0077	0.0201	0.0029	0.8425	0.0039	0.0117	0.0006	0.0118	0.0037	0.0478	0.0039	0.0074	0.0013	0.0035	0.0001	0.0078	0.0000
M	0.0003	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0006	0.0000	0.0004	0.0002	0.0003	0.0515	0.0363	0.0654	0.1162	0.0445	0.0435	0.0133	0.1312	0.0103	0.0014	0.3432	0.0030	0.0059	0.0002	0.0217	0.0024	0.0180	0.0034	0.0041	0.0006	0.0023	0.0001	0.0791	0.0000
N	0.0003	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0005	0.0000	0.0004	0.0002	0.0002	0.0436	0.0413	0.0587	0.1532	0.0818	0.0892	0.0111	0.1740	0.0062	0.0009	0.2110	0.0031	0.0040	0.0001	0.0208	0.0036	0.0107	0.0043	0.0046	0.0005	0.0035	0.0001	0.0716	0.0000
O	0.0004	0.0004	0.0002	0.0001	0.0002	0.0001	0.0001	0.0000	0.0007	0.0000	0.0004	0.0003	0.0003	0.0313	0.0194	0.0384	0.0536	0.0139	0.0106	0.0086	0.0614	0.0128	0.0019	0.6109	0.0043	0.0092	0.0006	0.0150	0.0050	0.0355	0.0054	0.0078	0.0011	0.0048	0.0001	0.0450	0.0000
P	0.0003	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002	0.0000	0.0006	0.0000	0.0004	0.0002	0.0003	0.0368	0.0319	0.0489	0.1066	0.0501	0.0538	0.0095	0.1224	0.0087	0.0013	0.3767	0.0044	0.0061	0.0003	0.0294	0.0030	0.0208	0.0059	0.0047	0.0008	0.0031	0.0001	0.0719	0.0000
Q	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0008	0.0000	0.0004	0.0002	0.0003	0.0544	0.0308	0.0658	0.0884	0.0199	0.0125	0.0142	0.0978	0.0154	0.0020	0.4659	0.0021	0.0078	0.0002	0.0135	0.0025	0.0237	0.0027	0.0047	0.0007	0.0024	0.0001	0.0697	0.0000
R–S	0.0004	0.0002	0.0001	0.0001	0.0002	0.0001	0.0003	0.0000	0.0008	0.0000	0.0005	0.0003	0.0003	0.0695	0.0428	0.0858	0.1174	0.0276	0.0189	0.0182	0.1312	0.0065	0.0010	0.2459	0.0043	0.0049	0.0002	0.0486	0.0082	0.0140	0.0110	0.0095	0.0007	0.0083	0.0001	0.1217	0.0000
T	0.0008	0.0001	0.0002	0.0003	0.0003	0.0000	0.0001	0.0001	0.0002	0.0000	0.0004	0.0003	0.0003	0.0418	0.0213	0.0487	0.0656	0.0182	0.0143	0.0105	0.0774	0.0033	0.0008	0.5661	0.0030	0.0065	0.0011	0.0139	0.0027	0.0293	0.0033	0.0068	0.0000	0.0027	0.0002	0.0593	0.0000

Notes: This table reports the third part of the calculated parameters for the 37-sector model.

Table E.5: Brown intermediate inputs ratio

Code	Type of sector	Brown ratio
A	brown	0.73
B	brown	0.65
C10–C12	brown	0.75
C13–C15	brown	0.66
C16	brown	0.75
C17	brown	0.76
C18	brown	0.66
C19	brown	0.66
C20	brown	0.73
C21	brown	0.54
C22	brown	0.74
C23	brown	0.70
C24	brown	0.80
C25	brown	0.77
C26	brown	0.58
C27	brown	0.69
C28	brown	0.72
C29	brown	0.73
C30	brown	0.71
C31-32	brown	0.63
C33	brown	0.68
D	brown	0.81
E	brown	0.65
F	brown	0.72
G	green	0.54
H	brown	0.71
I	green	0.66
J	brown	0.63
K	green	0.19
L	brown	0.50
M	green	0.33
N	green	0.38
O	green	0.52
P	green	0.46
Q	green	0.44
R–S	green	0.42
T	green	0.56

Notes: This table reports sector types and the ratio of brown intermediate inputs in total intermediate inputs at NACE level 2 sectors.

F Data

In this appendix, we describe the data utilised for the calculation of empirical moments of the euro area economy.

All macroeconomic growth rates dx_t are calculated by computing the quarterly log growth rate and then annualising the quarterly growth rates by summing up four consecutive quarterly growth rates using the following data:

1. real GDP Y_t – "gross domestic product at market prices";
2. consumption C_t – "household and NPISH final consumption expenditure";
3. investment I_t – "gross fixed capital formation".

All these variables are measured using chain linked volumes (2015), millions of euro, seasonally and calendar adjusted data, euro area – 19 countries (from 2015) and have been downloaded from Eurostat. The ratio I_t/Y_t is computed using the same data.

Aggregate inflation Π_t is given by the monthly data series "harmonised index of consumer prices (HICP) - all items, measured by growth rate on previous period (t/t-1), neither seasonally adjusted nor calendar adjusted data, euro area – 19 countries (from 2015)", from Eurostat.

The nominal risk-free interest rate i_t is identified in the data by using the daily time series "ECB interest rate on deposit facility", available from the ECB.

The nominal deposit interest rate R_t^D is identified in the data by using the monthly time series "euro area (changing composition), annualised agreed rate (AAR)/narrowly defined effective rate (NDER), credit and other institutions (MFI except MMFs and central banks) reporting sector – Overnight deposits, total original maturity, new business coverage, non-financial corporations and households (S.11 and S.14 and S.15) sector, denominated in euro", available at the ECB Statistical Data Warehouse, only from 2003:M1 onward though.

The nominal loan interest rate R_t^i is identified in the data by using the monthly time series "euro area (changing composition), annualised agreed rate (AAR) / narrowly defined effective rate (NDER), credit and other institutions (MFI except MMFs and central banks) reporting sector – loans, total original maturity, outstanding amount business coverage, non-financial corporations (S.11) sector, denominated in euro", available at the ECB Statistical Data Warehouse, only from 2003:M1 onward though.

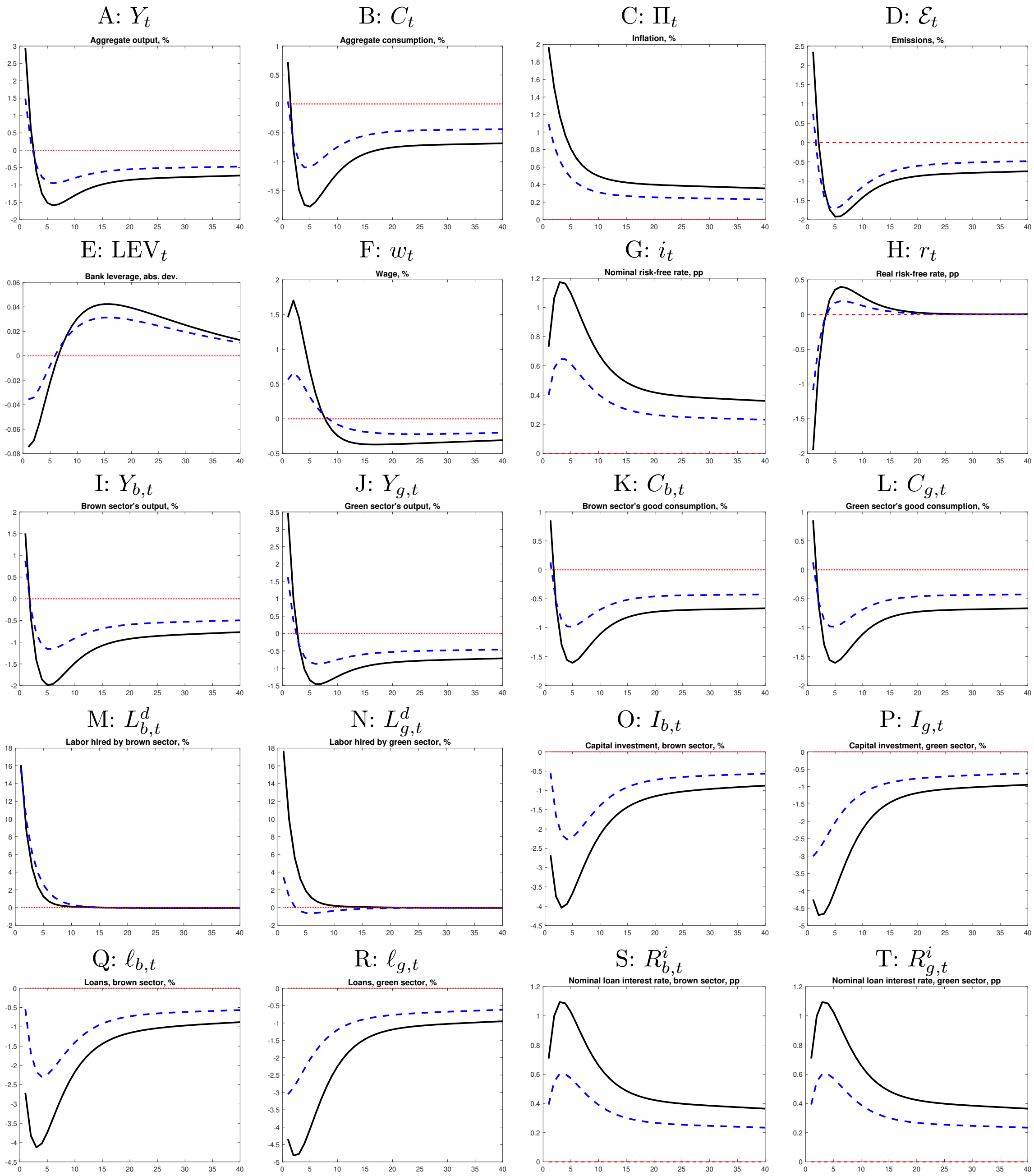
The loan to annualised GDP ratio $\ell_t/(4Y_t)$ is computed using quarterly data for nominal GDP Y_t, i.e. "gross domestic product at market prices, current prices, millions of euro, seasonally and calendar adjusted data, euro area – 19 countries (from 2015)", from Eurostat and quarterly data on "euro area (changing composition), outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector – loans, total maturity, all currencies combined – domestic (home or reference area) counterpart, non-MFI sector, denominated in euro, data neither seasonally nor working day adjusted, end of period (E), millions of euro" from the ECB Statistical Data Warehouse.

Bank leverage is computed as the weighted average leverage ratio of MFI and non-MFI leverage using quarterly data from Eurostat on "Financial balance sheets".

G Additional Benchmark Impulse Response Functions

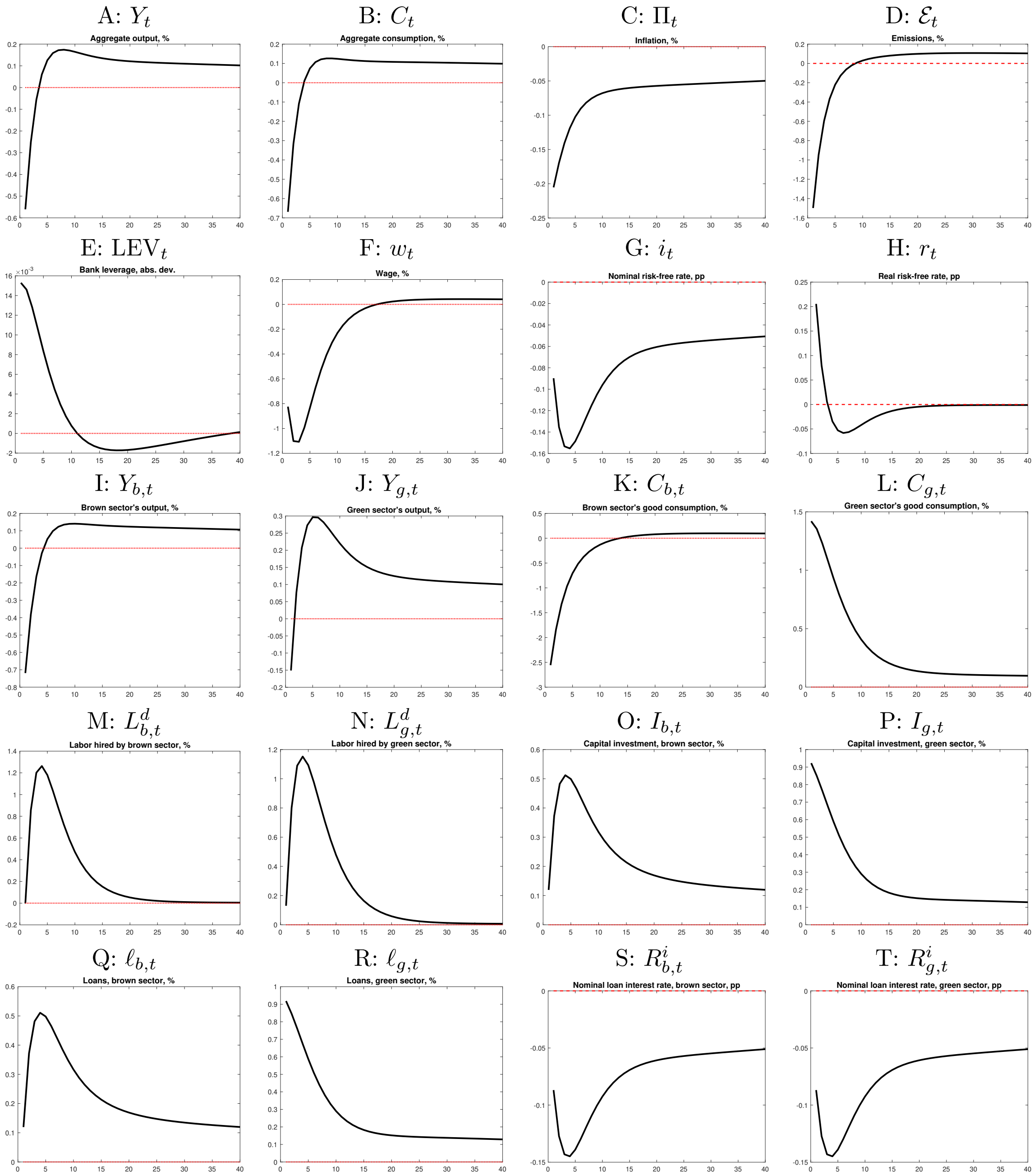
In this section, we provide additional impulse response functions for the benchmark model.

Figure G.1: Impulse response functions – capital utilisation rate shocks



Notes: This figure depicts impulse response functions for exogenous declines of 10% in logarithmic terms in capital utilisation rates in period 1. The black solid lines correspond to the simulation that sees an exogenous decline in the capital utilisation rates of all sectors, while the blue dashed lines depict the economic effects of a decline in the capital utilisation rates of the brown sectors only (see Table E.2 for the classification of sectors into brown and green).

Figure G.2: Impulse response functions – brown consumption tax shock



Notes: This figure depicts impulse response functions for an exogenous increase of 5 percentage points in the consumption tax rates for goods produced by brown sectors in period 1.

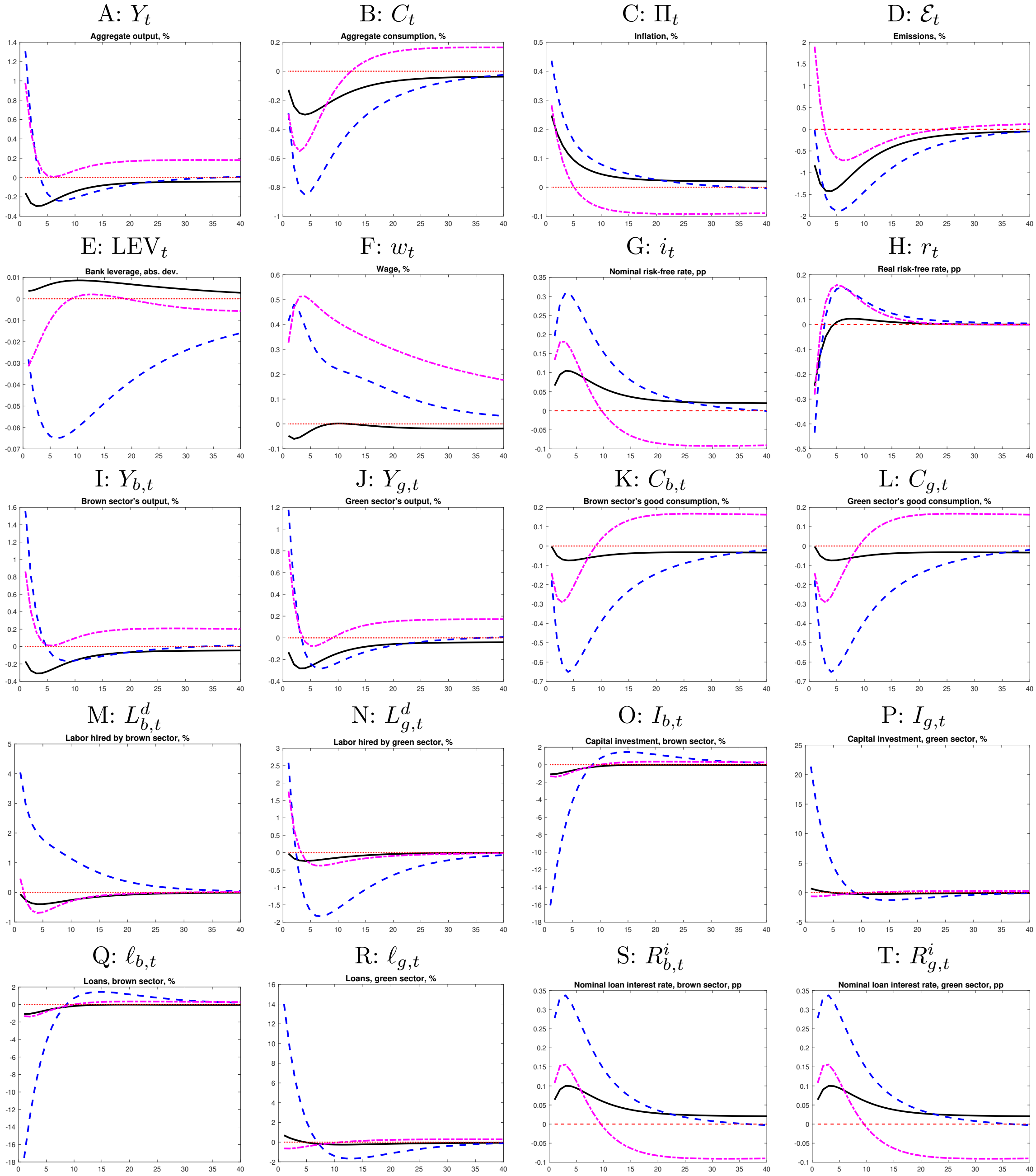
H Model without Abatement Channel

In this section, carbon tax simulations are shown for the model where intermediate goods producers cannot engage in abatement activities.

This implies setting $\psi_{s,t}^{A} \equiv 0$ and $X_{s,t}^{A} \equiv 0$ in the model to replace the first order condition (49) (and the corresponding real version of this equation) and the definition (45) in the set of equilibrium conditions. Furthermore, the term $\iota_{2s}(\psi_{s,t}^{A})^{\iota_{3s}}\mathring{Y}_{s,t}$ is erased from the sectoral market clearing condition (120) and the definition of $f_{3,s,t}$ in Equation (60); alternatively, one has to set $\iota_{2s} = 0$ for all $s = 1, \dots, S$.

Comparing Figure H.1 below to Figure 4 reveals that for all the revenue recycling scenarios the opportunity for firms to abate emissions generates additional emissions reductions in the order of 1–2%. Furthermore, it allows the revenue recycling scheme where public green capital is built with the carbon tax revenues to even feature a boost to economic output alongside lower emissions, while emissions increase in the short run without the abatement opportunity by almost 2%. Only the dynamics of emissions are considerably affected, while the other impulse responses do not show remarkable differences in the model without abatement.

Figure H.1: Impulse response functions – carbon tax shock and type of revenue recycling



Notes: This figure depicts impulse response functions for an exogenous increase in the carbon tax equal to 20 euro per ton of carbon (i.e. a doubling of the carbon tax from 20 to 40 euro) in all sectors in period 1. The black solid lines correspond to carbon tax revenue recycling in the form of a lump-sum transfer to households, the blue dashed lines to carbon tax revenue recycling in the form of investment subsidies to the firms in the green sectors, and the magenta dash-dotted lines to carbon tax revenue recycling in the form of investment in public green capital.

I Model without Intermediate Inputs Linkages

In this section, we provide impulse response functions in the equivalent model, where there are no input-output linkages in the intermediate goods sectors. Thus, input-output linkages can only be found in capital investments via the investment networks.

This implies that the intermediate goods production function for producer j is changed to the following simpler one:

$$Y_{s,j,t} = (1 + K^{p}_{g,t})^{\alpha_{gs}} A_{s,t} \mathrm{VA}_{s,t}, \tag{I.1}$$

$$\mathrm{VA}_{s,t} = \left(\alpha_s (u_{s,t} K_{s,j,t})^{(\gamma_s-1)/\gamma_s} + (1-\alpha_s)(L_{s,j,t})^{(\gamma_s-1)/\gamma_s}\right)^{\gamma_s/(\gamma_s-1)}. \tag{I.2}$$

All intermediate inputs, its prices, and related equations disappear from the model, i.e. one has to set $Z_{s,t} = 0$ and $Z_{r,t}(s)$ for all $s, r = 1, \ldots, S$ everywhere where these variables appear in the model, and the following equations are removed from the set of equilibrium conditions (including the real versions of these equations): (39), (42), (47). Furthermore, Equation (61) changes to:

$$\mathring{Y}_{s,t} = Y_{s,t}/\mathring{P}_{s,t} = (\mathring{P}_{s,t})^{-1}(1 + K^{p}_{g,t})^{\alpha_{gs}} A_{s,t} \mathrm{VA}_{s,t}. \tag{I.3}$$

Additionally, the first order conditions (46) and (48) simplify to (similar changes are applied to the real versions of these equations):

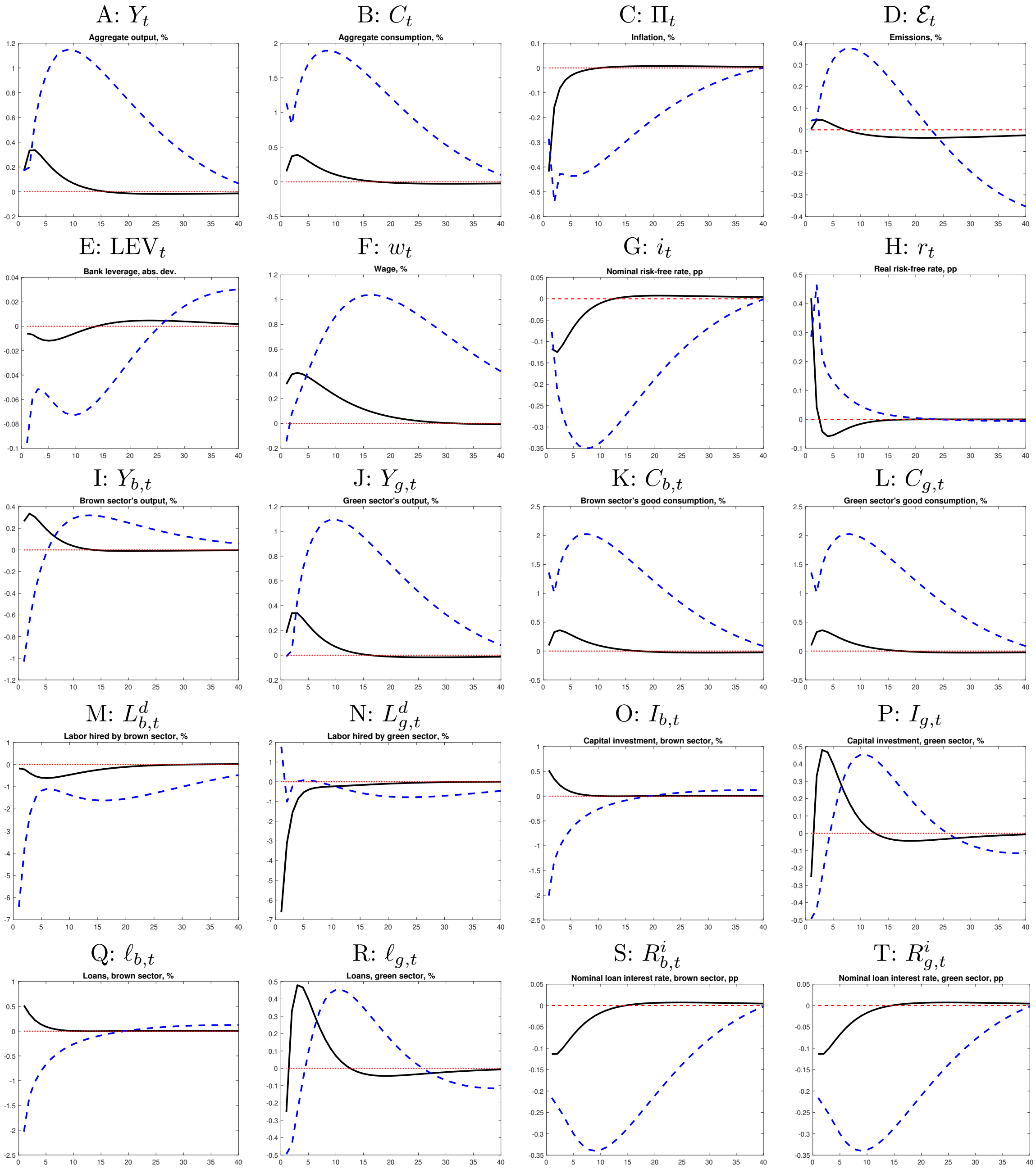
$$W_{s,t} = \frac{\mathrm{MC}_{s,t}(1-\alpha_s) Y_{s,t}}{\mathrm{VA}_{s,t}} \left(\frac{\mathrm{VA}_{s,t}}{L^{d}_{s,t}}\right)^{1/\gamma_s}, \tag{I.4}$$

$$R^{k}_{s,t} = \frac{\mathrm{MC}_{s,t} \alpha_s u_{s,t} Y_{s,t}}{\mathrm{VA}_{s,t}} \left(\frac{\mathrm{VA}_{s,t}}{u_{s,t} K_{s,t}}\right)^{1/\gamma_s}. \tag{I.5}$$

To let this alternative model reproduce similar moments as the benchmark model, the consumption and intermediate input tax rates $\bar{\tau}^{c}_{s}$ and $\bar{\tau}^{z}_{s}$ and the LIA constraint parameter χ_s are calibrated differently. The values chosen now are $\bar{\tau}^{c}_{s} = \bar{\tau}^{z}_{s} = 0.122$ and $\chi_s = 3.75$. This allows this model to still produce an implied steady-state labour income tax rate and total loans to annualised GDP ratio as the benchmark model. Thus, changes discussed below might not only be related to the absence of interlinkages in intermediate goods sectors but also to these changes in parameters. The parameters ζ_s and σ_s are not needed anymore, while the parameters α_s and γ_s remain to be set as before. The parameters α_s do not change, since we assume that the share of intermediate inputs in the benchmark model is distributed according to the original capital and labour shares α_s and $1 - \alpha_s$.

The most interesting changes are visible for the scenarios featuring the green technology shock and capital utilisation rate shocks. The results from these scenarios in the

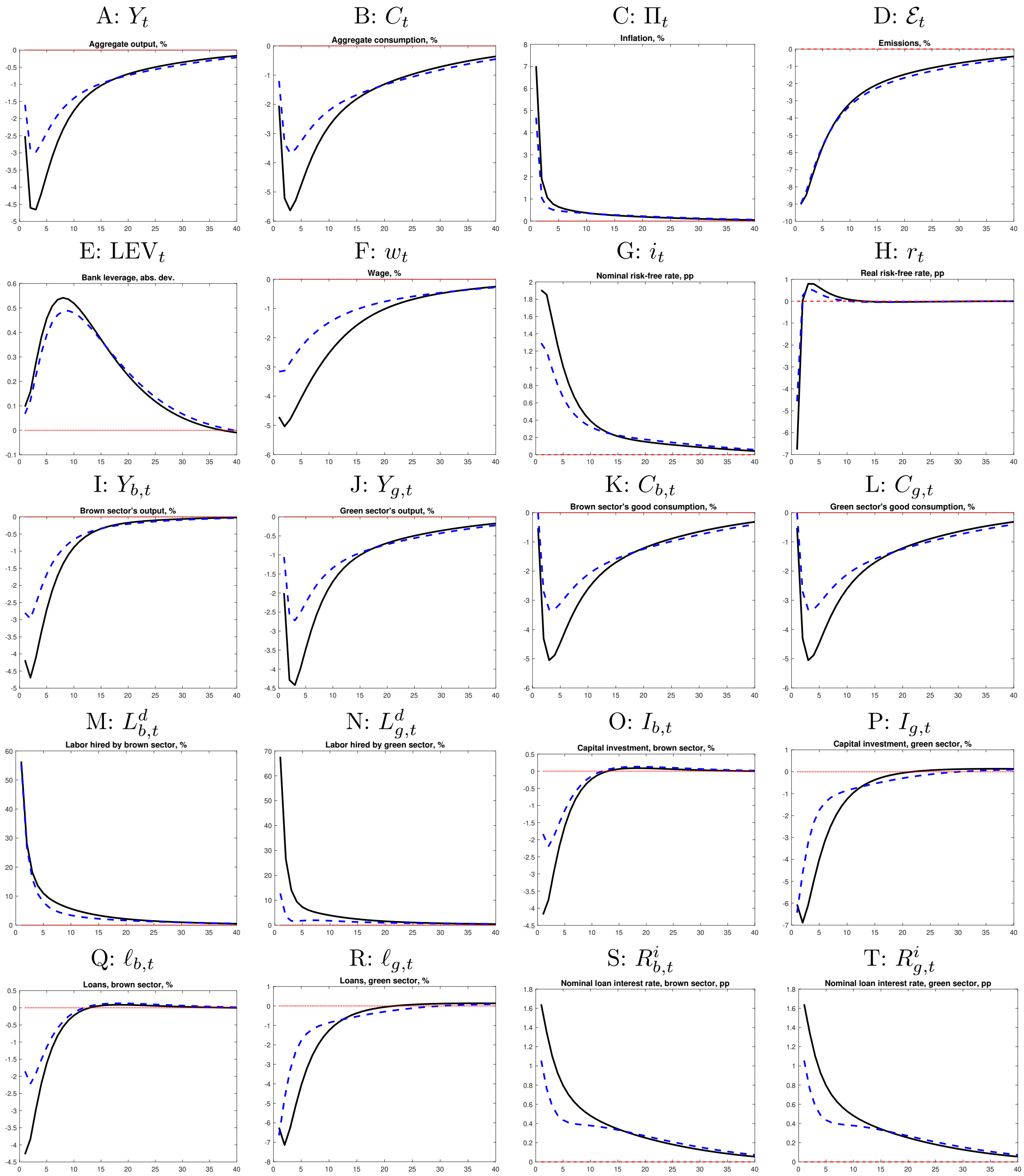
Figure I.1: Impulse response functions – green technology shock, building public capital



Notes: This figure depicts impulse response functions for several different shocks in period 1. The black solid lines depict impulse response functions for an exogenous increase of 3.5 percentage points in the total factor productivity processes of the green sectors. The blue dashed lines correspond to the government issuing green public bonds for building public green capital in the amount of 5% of aggregate private investment.

model without intermediate input linkages are depicted in Figures I.1 and I.2. First, comparing Figure I.1 to Figure 5 reveals that the green technology shock is expansionary in the model without input-output linkages in the intermediate goods sectors, while it was recessionary in the short run in the benchmark model. Moreover, the effects of building public capital are larger without these interlinkages. This can be explained by

Figure I.2: Impulse response functions – capital utilisation rate shocks



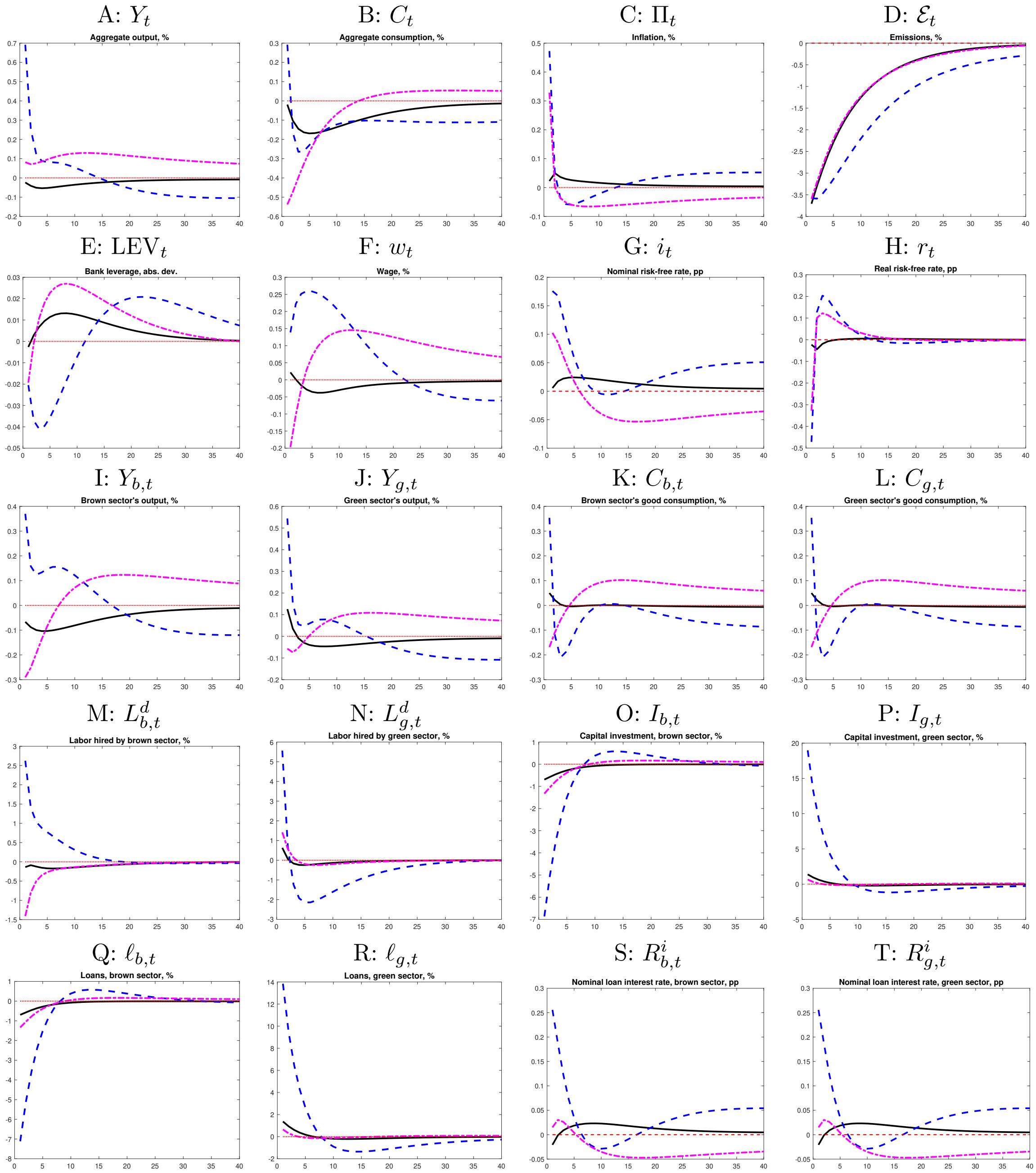
Notes: This figure depicts impulse response functions for exogenous declines of 10% in logarithmic terms in capital utilisation rates in period 1. The black solid lines correspond to the simulation that sees an exogenous decline in the capital utilisation rates of all sectors, while the blue dashed lines depict the economic effects of a decline in the capital utilisation rates of the brown sectors only (see Table E.2 for the classification of sectors into brown and green).

supply-side restrictions in the benchmark model. The green technology shock is not expansionary at first since the supply of intermediate inputs from the brown sectors takes time to increase and thus the economy channels funds to household consumption to obtain higher utility and investments to increase the supply of brown intermediate inputs in the longer run. These redistribution activities harm economic growth initially despite the productivity increase in the green sectors. In the model without interlinkages, the benefits of higher productivity can be fully enjoyed by the green sectors instead and due to the incentive to reallocate labour from the green to the brown sectors are also enjoyed by the brown sectors. The capital utilisation rate shocks imply more negative reactions in the longer run and negative instead of positive reactions in the short run in the model without interlinkages as can be seen from comparing Figure I.2 to Figure G.1. In the model with interlinkages, the lower capital utilisation in the sectors propagates through the intermediate inputs network and its negative effects are shared collectively among all sectors. This is why capital investments decrease less, inflation increases less, and the increased labour supply can be better put to use by the intermediate goods firms, as compared to the effects in the model without intermediate input interlinkages. Without the interlinkages, the capital investments decrease much more in the affected sectors and inflation increases five times more due to each sector having to face the burden of lower capital utilisation alone, which due to the ensuing strong monetary policy tightening implies larger output losses, especially in the short run when inflation increases by 6% or 10%, depending on which sectors are affected by lower capital utilisation.

The effects of investment tax and subsidy shocks are also changed considerably in favour of these policies (Figures I.3 and I.4 vis-á-vis Figures 4 and 6 for the benchmark model). Generally, brown investment taxes, green investment subsidies, and the carbon tax revenue recycling scheme that uses the carbon tax revenues to finance green investment subsidies are performing much better by producing larger green transition activities and greater benefits for the green sectors. However, this does not come unexpected since the share of capital has become larger and thus investment dynamics play a larger role in the model than before. Additionally, benefits to one sector only accrue to this sector and not as before significantly also to the other sectors from which this sector uses a large share of intermediate inputs in the benchmark model.

In particular, the carbon tax revenue recycling scheme that uses the revenues to finance green investment subsidies also breaks the trade-off between economic growth and an emissions reduction in the short and medium run, since aggregate output expands while emissions considerably decrease (also in the long run). The emissions reduction is even the highest in this carbon tax revenue recycling scenario, and the reduction of output in the long run is rather small. Similarly, the introduction of an investment tax in the brown sectors induces an aggregate output extension in the short to medium run while reducing emissions significantly, which originates mostly from the expansion of green production activities (see Panel J in Figure I.4). The production in the brown sectors is not harmed for very long due to the uniform decrease in loan costs in all sectors (Panels S and T). In addition, the fiscal neutral combination of brown investment taxes and green investment subsidies also breaks the aforementioned trade-off between economic growth and emissions reductions in a similar way with expansionary effects until quarter 16 after

Figure I.3: Impulse response functions – carbon tax shock and type of revenue recycling

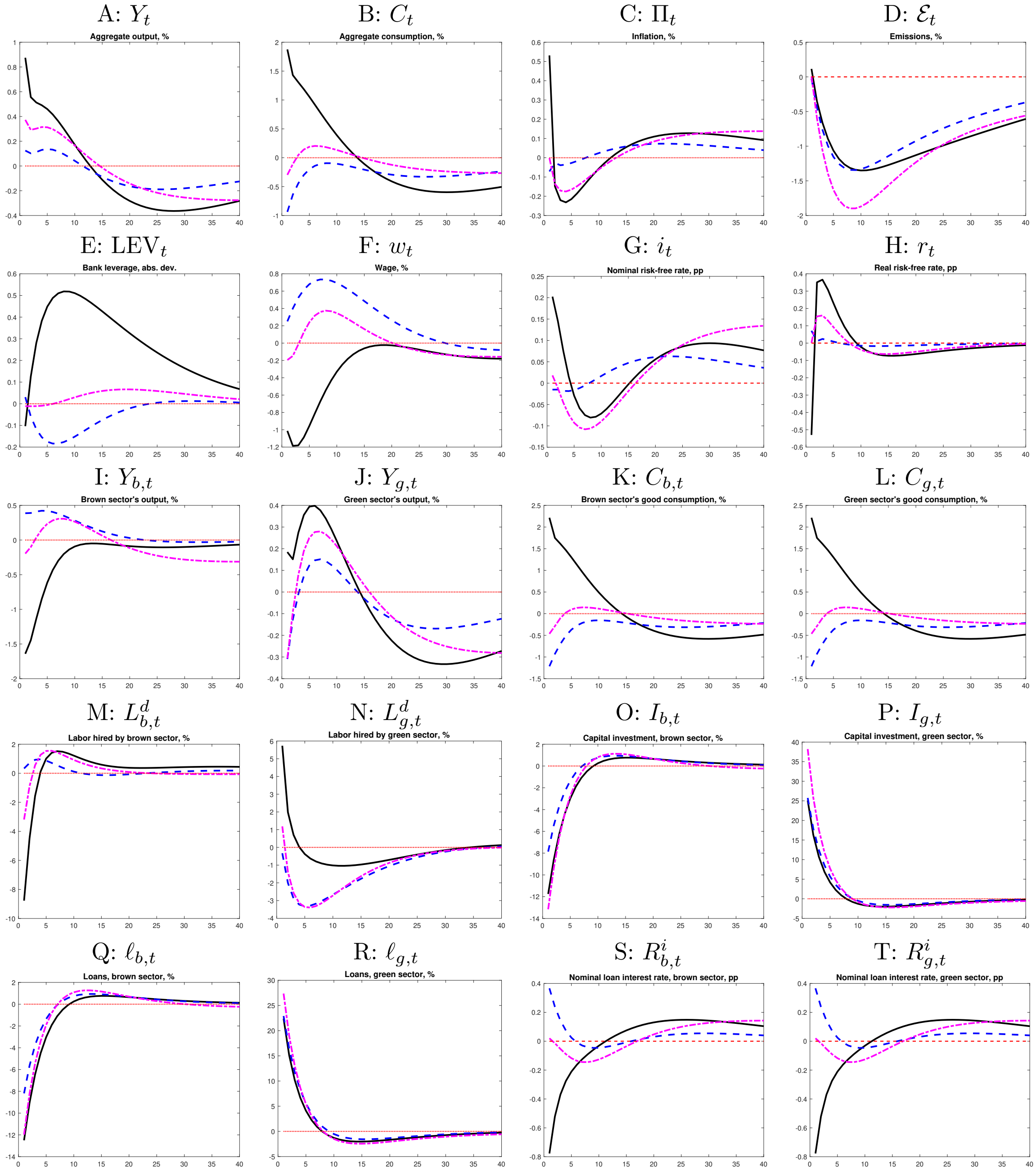


Notes: This figure depicts impulse response functions for an exogenous increase in the carbon tax equal to 20 euro per ton of carbon (i.e. a doubling of the carbon tax from 20 to 40 euro) in all sectors in period 1. The black solid lines correspond to carbon tax revenue recycling in the form of a lump-sum transfer to households, the blue dashed lines to carbon tax revenue recycling in the form of investment subsidies to the firms in the green sectors, and the magenta dash-dotted lines to carbon tax revenue recycling in the form of investment in public green capital.

the shock and a large emissions reduction, thereby restoring the favourable outcome of this fiscal policy that we have established in our previous work using a model without financial intermediaries (Grüning and Kantur, 2023).

In the absence of an intermediate input network, the responses of output and investment-

Figure I.4: Impulse response functions – investment tax/subsidy shocks



Notes: This figure depicts impulse response functions for exogenous changes in investment tax rates. The black solid lines correspond to the simulation that sees an exogenous increase of 5 percentage points in the investment tax rates of the brown sectors, while the blue dashed lines depict the economic effects of an exogenous decrease of 5 percentage points in the capital investment tax rates (i.e. an investment subsidy) of the green sectors in period 1. Finally, the magenta dash-dotted lines correspond to a fiscal budget-neutral combination of the two aforementioned simulations.

related variables to financial regulation shocks are generally more subdued, indicating a reduced level of amplification. On the other hand, price-related variables exhibit more pronounced differences, both in terms of magnitude and direction. After an absconding rate shock in the brown sector under the scenario without the intermediate input network, we observe a limited decline in brown loan demand, compared to the case with the network (Figures I.5 and 2). When the intermediate input network is absent, firms are less able to manage their input costs effectively, resulting in a more significant contraction in labour demand than in the original scenario. Additionally, the fall in inflation is more pronounced, leading to a larger decrease in interest rates, which further exacerbates the decline in banks' net worth.

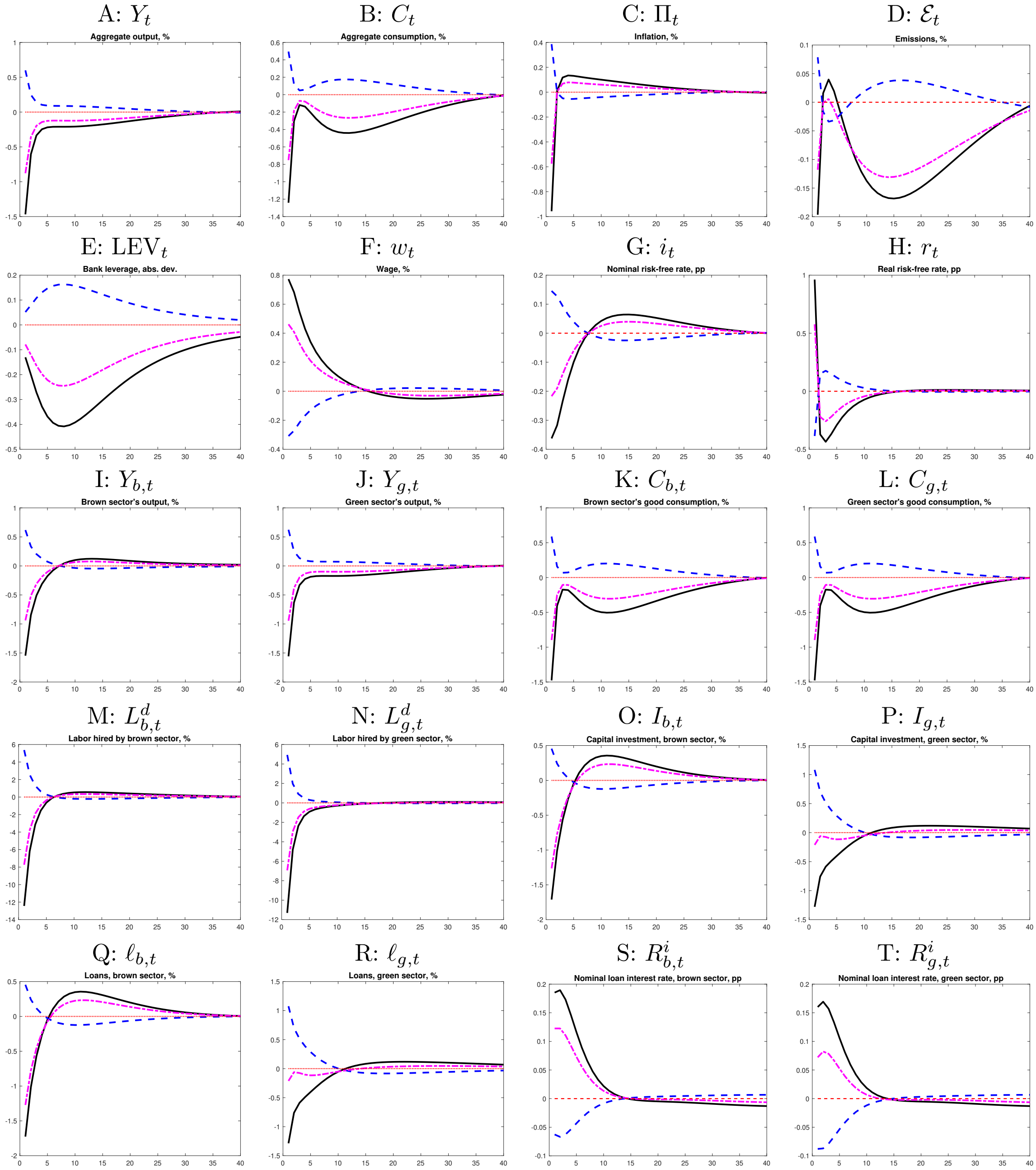
The sharper reduction in banks' net worth under the no-network scenario leads to a more significant contraction in loan supply. This occurs because the shock is transmitted predominantly through the investment network, where the reduction in loan supply exceeds the decline in loan demand. Consequently, loan rates of both brown and green loans increase as the investment network remains intact, ensuring that the loan market continues to function as an integrated system. The green sector is also affected through the investment network. Initially, green investment declines due to elevated loan rates, but a quick recovery follows, even resulting in a slight increase in green output, which can be interpreted as an indication of a green transition. However, since green investment relies on brown investment goods, brown investment also rises, leading to an initial increase in emissions. In the long run, however, we observe a decline in emissions, driven by the effects of the green transition.

A negative shock to the absconding rate in the green sector increases demand for green loans, which in turn boosts investment and green output. Without the intermediate input network, the allocation of inputs changes in the no intermediate input network case, leading to a sharper decline in labour demand. Inflation rises, followed by an increase in interest rates. As a result, banks' net worth improves, leading to an expansion in loan supply, and loan interest rates fall. The availability of cheaper brown and green loans stimulates investment in both sectors, driving up output. While emissions initially increase, they eventually decline as the rise in green output surpasses that of brown output. In this scenario, the increase in green output does not contribute to additional emissions, since the intermediate input network channel is closed.

In the absence of the intermediate input network, the investment network plays a more prominent role, making the loan market more significant in driving economic dynamics. With firms facing greater limitations in the allocation of inputs, price adjustments become less efficient, resulting in increased price volatility. As a result, the overall response of the economy to shocks is shaped more by the strength of the investment network, which amplifies the effects on loan supply and demand.

In Figure I.6, we examine the impact of Green QE, Brown QT, and the combined policy effects in the absence of the intermediate input network. When the central bank purchases green bonds, it exerts downward pressure on green bond yields, reducing the cost of borrowing for green projects. As a result, green loans increase, followed by a rise in green investment and green output. Similar to absconding rate shocks, the magnitude of responses of these variables are smaller compared to Figure 3. With the investment net-

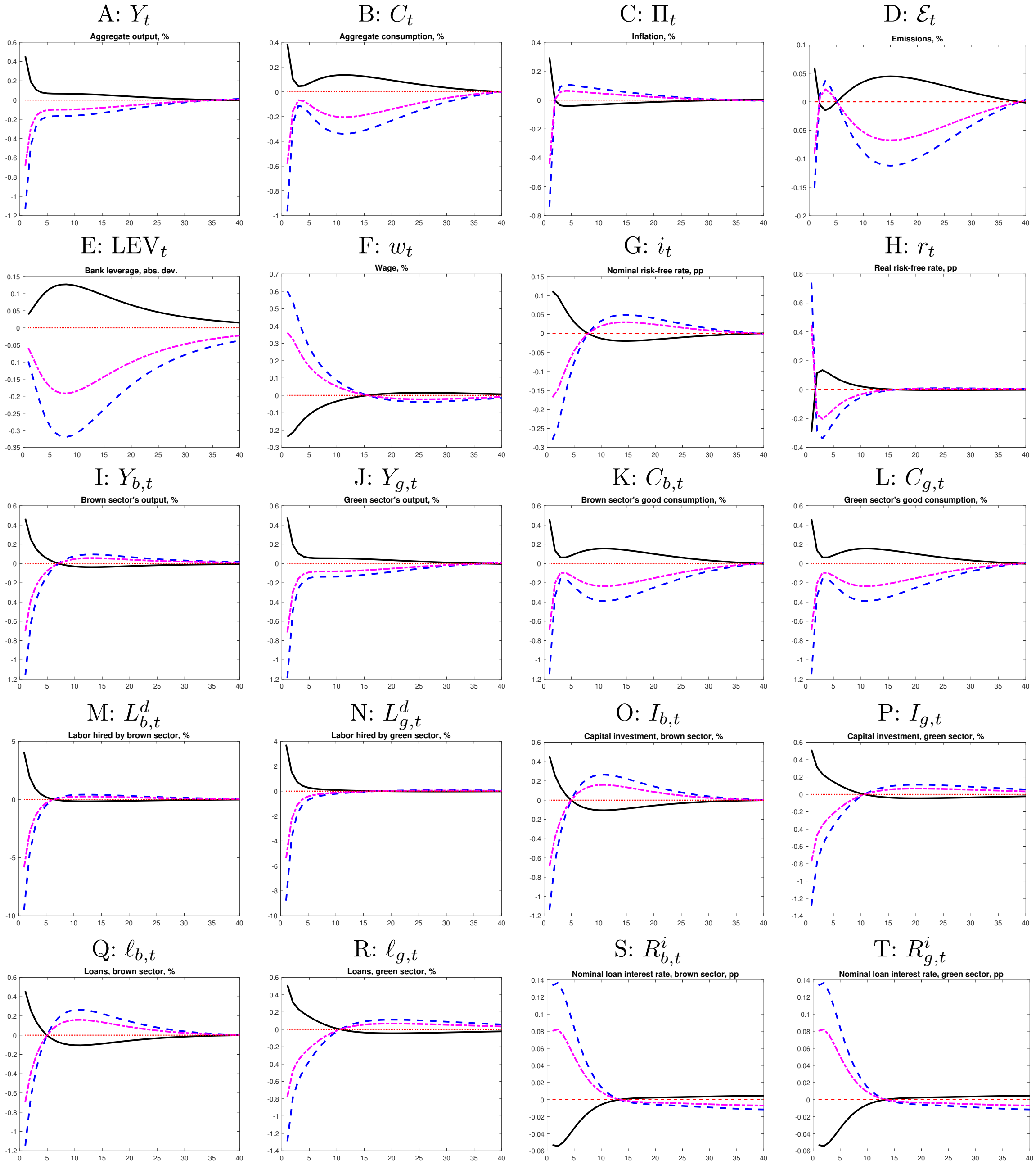
Figure I.5: Impulse response functions – absconding rate shocks



Notes: This figure depicts impulse response functions for exogenous changes in absconding rates. The black solid lines correspond to the simulation that sees an exogenous increase of 10 percentage points in the absconding rates of the brown sectors, while the blue dashed lines depict the economic effects of an exogenous decrease of 10 percentage points in the absconding rates of the green sectors in period 1. Finally, the magenta dash-dotted lines correspond to a combination of the two aforementioned simulations.

work still in place, demand for brown investment also rises, leading to increased demand for brown loans. In the absence of the intermediate input network, the labour demand increases more significantly due to the less efficient allocation of inputs. Consequently, inflation rises more than in the original scenario, prompting a larger increase in interest rates. The expansion of bank net worth boosts loan supply, causing loan rates to fall.

Figure I.6: Impulse response functions – QE/QT shocks



Notes: This figure depicts impulse response functions for QE and QT shocks by the monetary authority in period 1. For the black solid lines, the central bank buys an additional 5% of the outstanding corporate bonds in the green sectors to implement a Green QE programme. For the blue dashed lines, the central bank sells 5% of the outstanding corporate bonds in the brown sectors that are on its balance sheet, i.e. a Brown QT shock. The magenta dash-dotted lines combine the aforementioned Green QE and the Brown QT shocks.

In this case, the increase in green output surpasses that of brown output, as the absence of the intermediate input network shifts the dynamics. As a result, emissions decrease in the medium run, driven by the stronger growth in green output. In another scenario, where the central bank implements Brown QT by raising the cost of brown loans, we observe similar but opposite effects due to the interconnectedness of sectors through the investment network. The key difference is a sharper decline in output for the green sector. This outcome is driven by two factors: the reduced demand for green investment goods from the brown sector and the higher loan rates, which constrain green sector investment. Similarly, the combined policy implementation highlights the heightened significance of the investment network in the absence of the intermediate input network. We observe an increase in loan rates, accompanied by a decline in both sectoral and aggregate output levels. The drop in inflation is more pronounced, and the monetary policy's response to falling prices effectively influences the loan market by expanding loan supply, which in turn puts additional downward pressure on loan rates. The overall impact is more contractionary compared to the original case we have in the analysis.

J Impulse Response Functions without Banks

In this section, we provide impulse response functions in the equivalent model, where there is no banking sector.

In order to eliminate the banking sector from the benchmark model, all equilibrium conditions (and their real versions) in Section 2.6 have to be erased from the equilibrium system. Moreover, the bank-related variables D_t, R_t^D, NW_t, Φ_t and Z_t^b have to be taken out from the household budget constraint. The loan-in-advance constraints (72) are taken out from the equilibrium system and the Lagrange multipliers attached to these constraints now obey $\mu_{s,t}^{\mathtt{LIA}} \equiv 0$ for all $s = 1, \ldots, S$. Additionally, the central bank variables $B_{b,t}^{cb}$, $B_{g,t}^{cb}$, $L_{s,t}^{i,cb}$, $s_{b,t}^{cb}$, $s_{g,t}^{cb}$, $s_{\ell,s,t}^{cb}$, RE_t, and $T_{cb,t}$ also have to be erased from the equilibrium system (e.g., government budget constraint), alongside the following equations (and their real counterparts): (93), (94), (95), (96), (97). The market clearing conditions in the bond and loan markets (Equations 116, 117, and 118), reduce to:

$$B_{b,t} = B_{b,t}^p, \tag{J.1}$$

$$B_{g,t} = B_{g,t}^p, \tag{J.2}$$

$$L_{s,t+1}^i = L_{s,t+1}^{i,p}, \quad s = 1, \ldots, S. \tag{J.3}$$

Finally, Equation (92) has to be erased from the equilibrium system and the Euler equation for deposits (9) becomes the following Fisher equation (with a similar change applied to the real version of this equation):

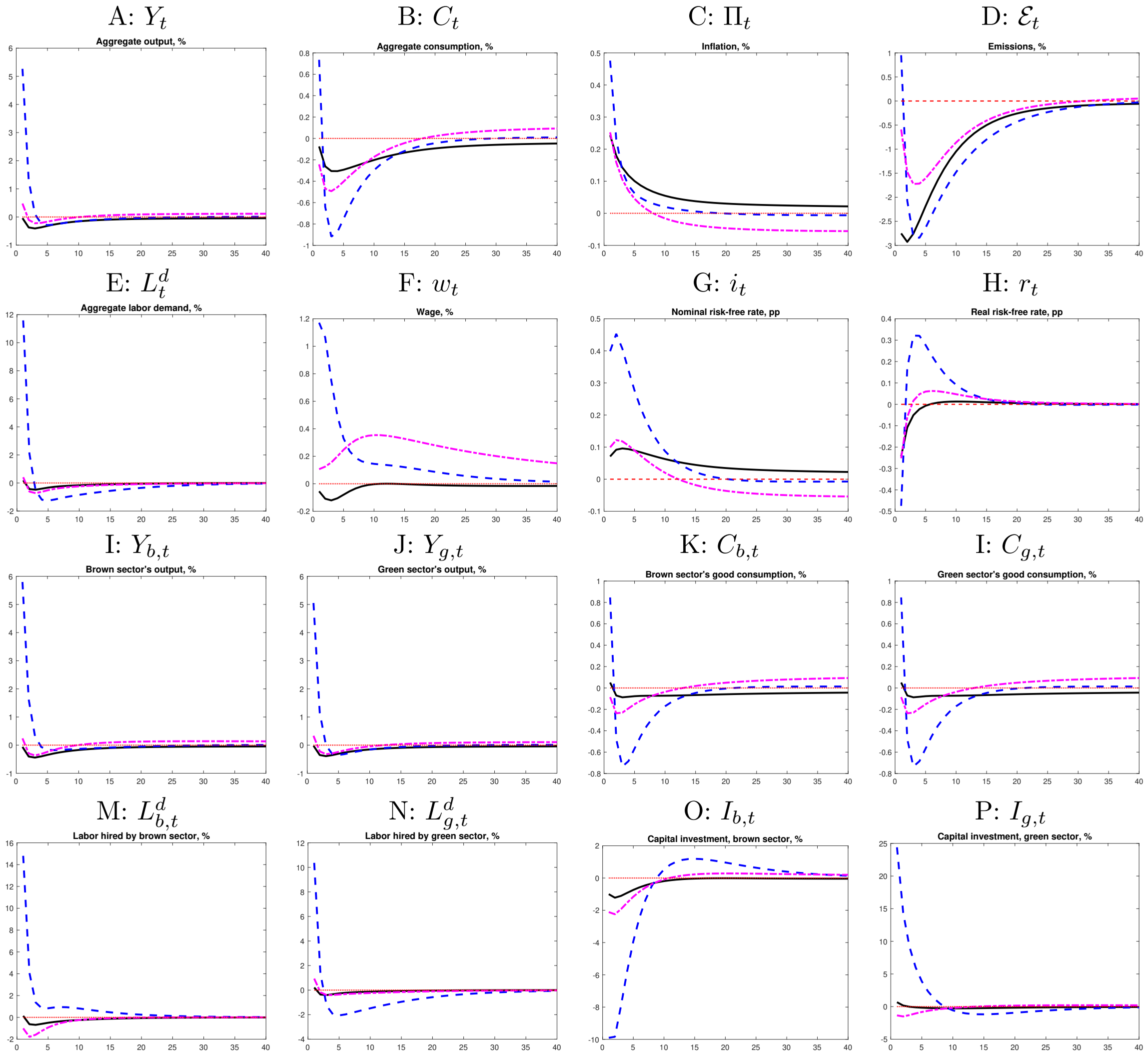
$$1 = \mathbb{E}_t[\mathbb{M}_{t,t+1}^{\$} i_t]. \tag{J.4}$$

To let this alternative model reproduce similar moments as the benchmark model, the consumption and intermediate input tax rates $\bar{\tau}_s^c$ and $\bar{\tau}_s^z$ are calibrated differently. The values chosen now are $\bar{\tau}_s^c = \bar{\tau}_s^z = 0.2578$. This allows this model to still produce an implied steady-state labour income tax rate as the benchmark model. Thus, changes discussed below might not only be related to the absence of interlinkages in intermediate goods sectors but also to these changes in parameters.

Comparing Figure J.1 to Figure 4 reveals that revenue recycling in the form of green investment subsidies work much better in terms of economic growth in the model without banks due to the direct link of investment and subsidies without banks acting as intermediaries that can smooth out this shock by increasing interest rates. Due to the strong boost of output in the short run the emissions increase on impact though and are only reduced in the longer run when the positive output effect dissipates. The other two revenue recycling schemes are not significantly affected by the presence of banks.

The green technology shock works a bit better without banks and also the responses

Figure J.1: Impulse response functions – carbon tax shock and type of revenue recycling



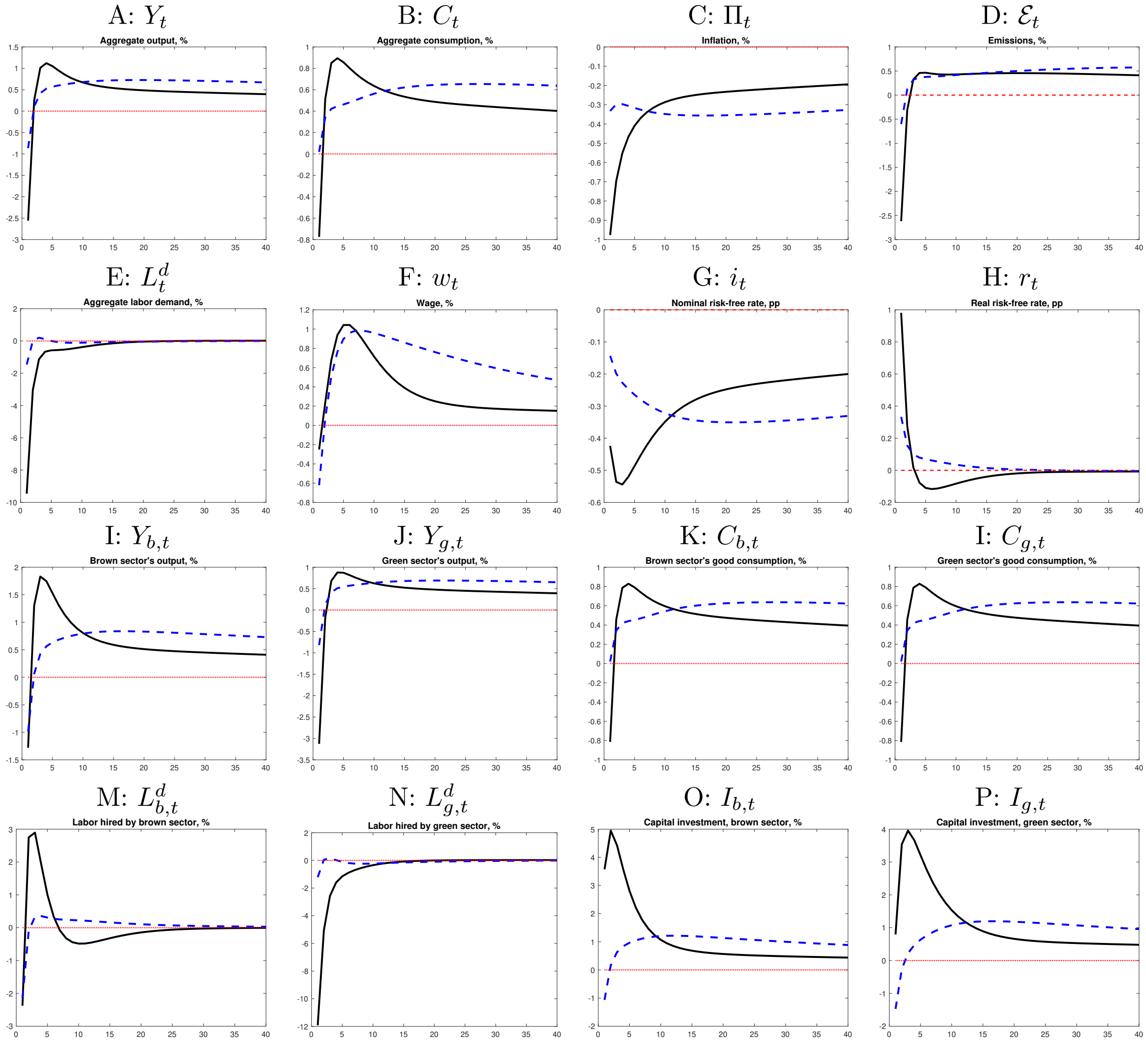
Notes: This figure depicts impulse response functions for an exogenous increase in the carbon tax equal to 20 euro per ton of carbon (i.e. a doubling of the carbon tax from 20 to 40 euro) in all sectors in period 1. The black solid lines correspond to carbon tax revenue recycling in the form of a lump-sum transfer to households, the blue dashed lines to carbon tax revenue recycling in the form of investment subsidies to the firms in the green sectors, and the magenta dash-dotted lines to carbon tax revenue recycling in the form of investment in public green capital.

are slightly amplified for building green public capital when comparing Figures J.2 and 5. This is again due to the economy being able to utilise the full potential of the shock without the banking sector as a smoothing channel in between.

The investment tax and subsidy shocks also become more powerful without banks due to banks adjusting the interest rates and thereby smoothing the shock when they are present and intermediating the investment expenditures in the model (see Figures 6 and J.3). Therefore, the output effects are amplified, implying that emissions increase when green investment subsidies are used as output is positively affected by green investment subsidies in the model without banks.

The effects of capital utilisation rate shocks become larger without banks, thereby

Figure J.2: Impulse response functions – green technology shock, building public capital

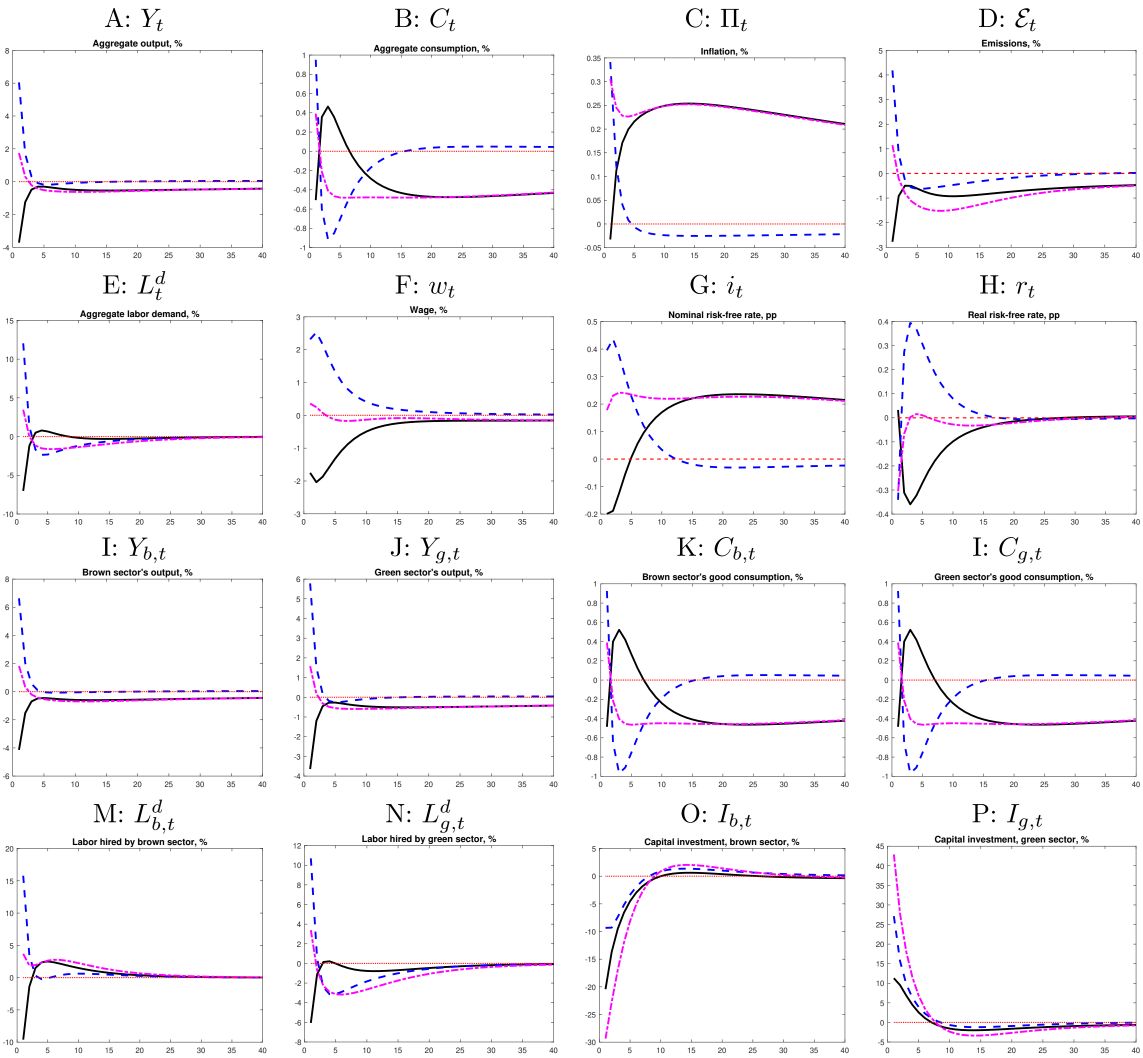


Notes: This figure depicts impulse response functions for several different shocks in period 1. The black solid lines depict impulse response functions for an exogenous increase of 3.5 percentage points in the total factor productivity processes of the green sectors. The blue dashed lines correspond to the government issuing green public bonds for building public green capital in the amount of 5% of aggregate private investment.

again pointing to the banks serving as a shock smoother in the economy (see Figures G.1 and J.4).

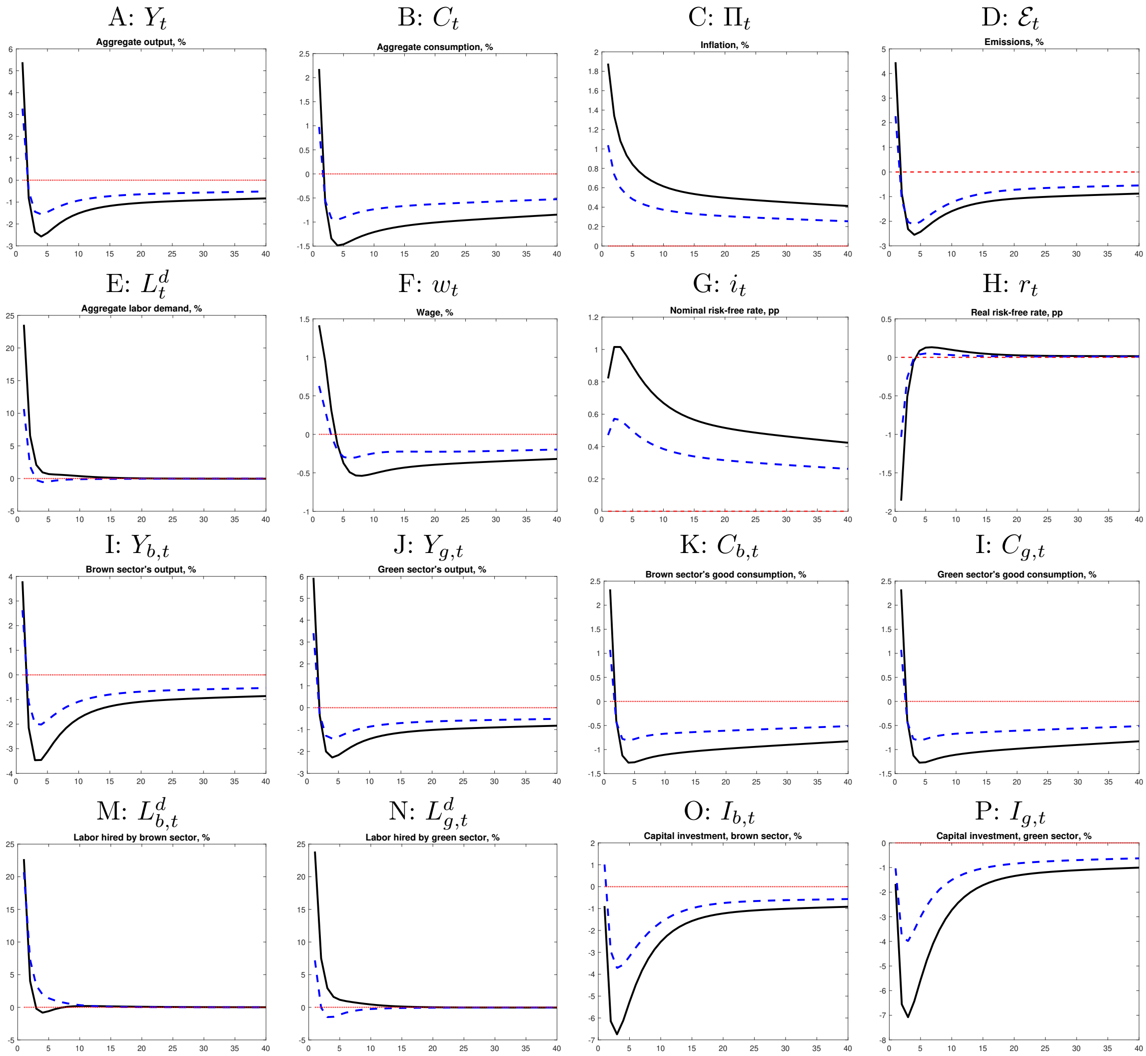
The consumption tax shock implies very similar effects with and without banks as apparent from a comparison of Figure J.5 with Figure G.2. Since banks only play a role in financing investment expenditures for firms, the consumption expenditure decisions of households are not affected by the banks' presence or absence.

Figure J.3: Impulse response functions – investment tax/subsidy shocks



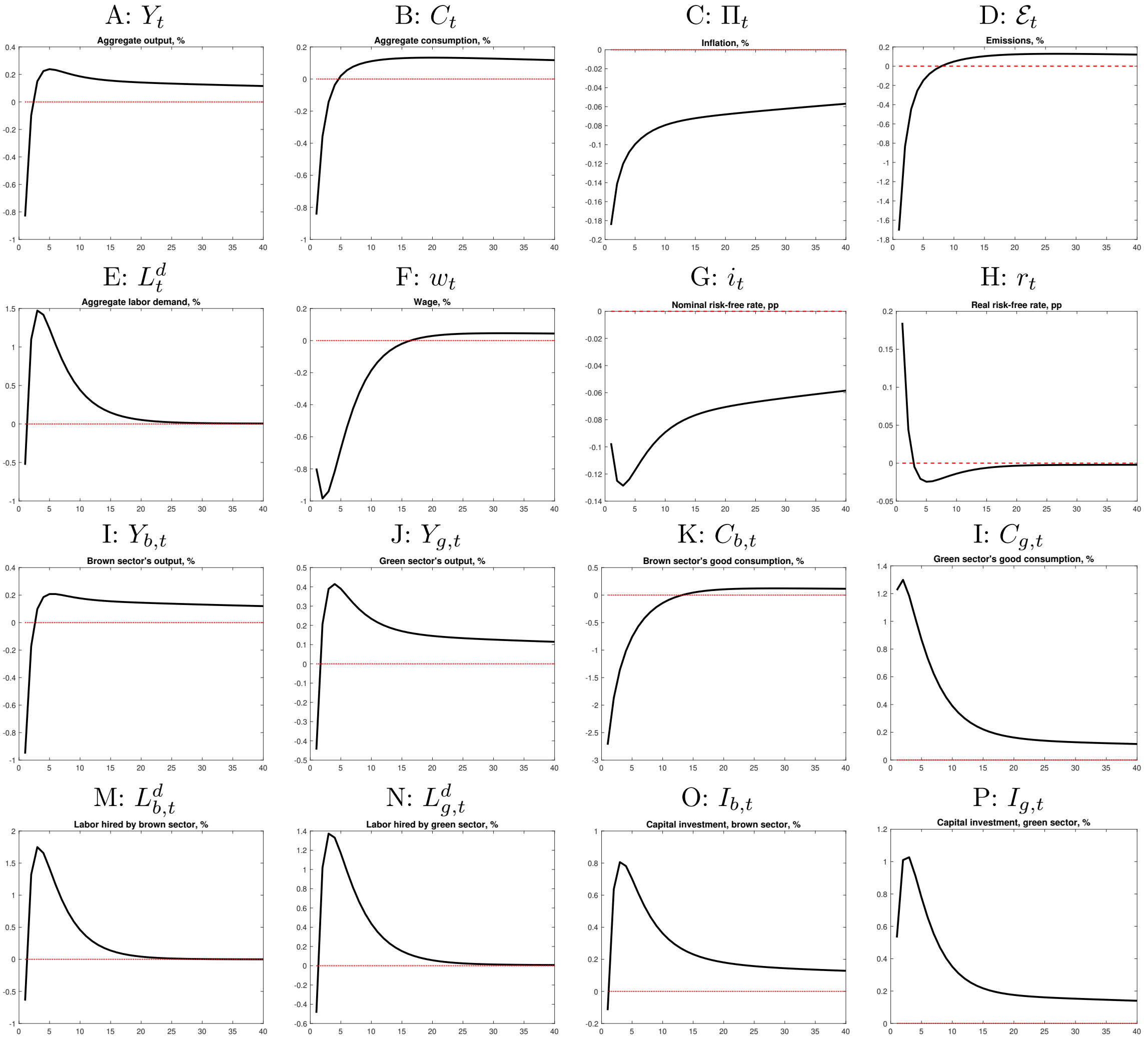
Notes: This figure depicts impulse response functions for exogenous changes in investment tax rates. The black solid lines correspond to the simulation that sees an exogenous increase of 5 percentage points in the investment tax rates of the brown sectors, while the blue dashed lines depict the economic effects of an exogenous decrease of 5 percentage points in the capital investment tax rates (i.e. an investment subsidy) of the green sectors in period 1. Finally, the magenta dash-dotted lines correspond to a fiscal budget-neutral combination of the two aforementioned simulations.

Figure J.4: Impulse response functions – capital utilisation rate shocks



Notes: This figure depicts impulse response functions for exogenous declines of 10% in logarithmic terms in capital utilisation rates in period 1. The black solid lines correspond to the simulation that sees an exogenous decline in the capital utilisation rates of all sectors, while the blue dashed lines depict the economic effects of a decline in the capital utilisation rates of the brown sectors only (see Table E.2 for the classification of sectors into brown and green).

Figure J.5: Impulse response functions – brown consumption tax shock



Notes: This figure depicts impulse response functions for an exogenous increase of 5 percentage points in the consumption tax rates for goods produced by brown sectors in period 1.