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Fiscal and macroprudential policies during an energy crisis

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Abstract

We construct a New-Keynesian E-DSGE model with energy disaggregation and financial intermediaries to show how energy-related fiscal and macroprudential policies interact in affecting the euro area macroeconomy and carbon emissions. When a shock to the price of fossil resources propagates through the energy and banking sector, it leads to a surge in inflation while lowering output and carbon emissions, absent policy interventions. By contrast, imposing energy production subsidies reduces both CPI and core inflation and increases aggregate output, while energy consumption subsidies only lower CPI inflation and reduce aggregate output. Carbon subsidies instead produce an intermediate effect. Given that both energy subsidies raise carbon emissions and delay the "green transition," accompanying them with parallel macroprudential policy that taxes dirty energy assets in bank portfolios promotes "green" investment while enabling energy subsidies to effectively mitigate the adverse effects of supply-type shocks, witnessed in recent years in the EA.

Keywords: DSGE model, energy sector, energy subsidies, financial frictions, macroprudential policy.

JEL classification: E52, E62, H23, Q43, Q58.

Non-technical summary

The spike in global fossil fuel prices that began in early 2022, driven largely by Russia's invasion of Ukraine, combined with ongoing pandemic-related disruptions such as rising food prices and supply chain bottlenecks, resulted in significant inflationary pressures across Europe. In many European countries, inflation surged by over 10%, placing a considerable burden on both households and firms. Policymakers responded with a variety of fiscal and monetary measures to alleviate the impact of higher energy costs, aiming to soften the blow of rising prices. However, these interventions pose a potential conflict with climate goals, particularly those tied to the European Commission's Green Deal, which aims to reduce carbon emissions and transition towards a greener economy.

This paper develops a dynamic stochastic general equilibrium (DSGE) model, calibrated to the Euro area (EA), to provide insights into the macroeconomic impacts of an increase in fossil fuel prices and the ensuing policy responses. The model includes a detailed breakdown of the energy sector and accounts for the role of financial intermediaries, offering a framework to evaluate policy choices in the context of energy price shocks. The analysis first explores the transmission channels through which an increase in fossil fuel prices affects the EA macroeconomy. It then examines the effectiveness of various fiscal measures, such as energy production and consumption subsidies, as well as carbon subsidies.

A key finding of the paper is that the impact of energy subsidies varies significantly depending on their design. Energy production subsidies, which lower the cost of energy for firms, reduce both the headline and core inflation, while boosting overall economic output. In contrast, energy consumption subsidies, which directly lower the price of energy for households, reduce headline inflation but also lower aggregate output by increasing the demand for energy without addressing the supply-side constraints. Carbon subsidies, which focus on reducing the price of carbon-intensive energy, produce an intermediate result, striking a balance between lowering inflation and output, but with less impact than production subsidies.

While energy subsidies can help mitigate inflationary pressures in the short term, they may come at the cost of the unintended consequence of slowing down the transition to a low-carbon economy by raising the production of energy. For instance, while energy production subsidies help lower costs for firms and boost output, they also slow the substitution towards cleaner energy by reducing the incentive for energy producers to adopt greener technologies. Similarly, carbon subsidies, while balanced in their impact on inflation and output, lead to higher emissions by making dirty energy more affordable.

Recognizing the trade-offs between short-term inflation stabilization and long-term environmental goals, the framework introduces targeted macroprudential policies to complement fiscal measures. In particular, a tax on dirty energy assets in bank portfolios can tilt investment away from carbon-intensive sectors and towards greener industries. This "emissions-prudential" policy helps reduce banks' exposure to dirty energy, supporting the financial sector's stability while also incentivizing green investment. By taxing dirty energy assets, policymakers can mitigate the increase in carbon emissions associated with energy subsidies and accelerate the transition towards a low-carbon economy. Overall, the framework underscores the importance of considering the sectoral and financial transmission mechanisms when designing policy responses during an energy crisis.

1 Introduction

Global fossil fuel prices started to soar in early 2022 upon Russia's invasion of Ukraine. Combined with the repercussions from the COVID-19 pandemic related to a rise in food prices and supply bottlenecks, overall consumer prices surged, with inflation rates increasing by more than 10% in many European countries. Fiscal and monetary policymakers in the euro area (EA) have responded with a broad range of relief measures to ease the burden of inflation and especially higher energy costs on households and firms. Yet, an unintended consequence of such measures is that they can counteract another important policy goal, that is, the reduction of carbon emissions as outlined for example in the European Commission's Green Deal.[1]

To comprehensively evaluate policy choice in the context of an exogenous fossil price increase, this paper presents a dynamic stochastic general equilibrium (DSGE) model with a disaggregated energy sector and financial intermediaries, and provides several insights. Our analysis first exposes the channels through which an exogenous increases in the price of fossil resources affects the EA macroeconomy, to then consider the effectiveness of a broad set of energy-related fiscal instruments – some utilized over 2021-2023 by EA policymakers – towards mitigating the inflationary and contractionary effects of increases in fossil prices. In particular, imposing energy production subsidies reduces both CPI and core inflation and increase aggregate output, while energy consumption subsidies only lower CPI inflation and also reduce aggregate output. Carbon subsidies instead produce an intermediate effect. Recognizing that such schemes may temporarily slow down the path towards decarbonisation, our analysis shows that in fact a parallel set of macroprudential policies aimed at taxing dirty energy assets in bank portfolios can effectively incentivize "green investment" and speed up the "green transition."

Our starting point is the standard New-Keynesian model of e.g., Christiano et al. (2005); Smets and Wouters (2007) with financial intermediaries as in Gertler and Karadi (2011), extended to include disaggregated energy-production and energy-consumption sectors. Energy enters our framework in a disaggregated fashion both on the consumption and production side.[2] This detailed setup is particularly useful allowing us to explore the effectiveness of different types of fiscal interventions, such as subsidies on the production and consumption of energy utilized by intermediate good firms for production and on consumption of households, but also carbon subsidies, which target the carbon-intensive nature of energy

[1]For more details on the European Union's Fit-for-55 package, see https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/.

[2]In particular, households consume a composite final consumption good, which consists of energy and a consumption good excluding energy. An intermediate good is produced by monopolistically competitive firms using value added (a capital-labour bundle) and an energy composite. Energy in turn is produced by perfectly competitive energy providers, who bundle clean and dirty energy inputs produced by monopolistically competitive dirty and clean energy producers, respectively. Each of the dirty and clean energy firms in turn produce their inputs by combining sector-specific value added with natural resources (fossils vs. renewables). As a by-product of production in the dirty energy sector, carbon emissions are released into the atmosphere.

production directly. The disaggregated multi-sector setup also allows for the possibility of sector-specific macroprudential policy where the central bank sets taxes or subsidies on sectoral bank assets to alter their weight in bank portfolios and alter the degree of sector-specific financial frictions.

In line with an adverse supply shock, our model suggests that an increase in the price of fossil resources produces inflationary and contractionary effects that are amplified as the shock propagates through the financial sector. The inflationary effects unfold as follows: Because energy is directly used in consumption, the increase in the fossil resource price feeds directly through to the price of the final consumption good, causing CPI inflation to surge. Core inflation (i.e. inflation excluding energy) also rises as intermediate good producers, who utilize a bundle of clean and dirty energy for production of the intermediate good, experience an increase in their marginal costs. The contractionary real effects entail a fall in current and expected future real income and profitability. These effects cause households to cut back on consumption and non-financial firms to cut back on investment.

Several straight-forward implications for the energy mix in production and investment arise. At the sectoral level, following an increase in the price of dirty energy, energy producers substitute away from utilizing more costly dirty energy and into utilizing now relatively less costly clean energy for the production of the aggregate energy good used in intermediate good production. Given the imperfect substitutability across energy types, the lower use of dirty energy for production contributes to lowering carbon emissions in the medium term. At the same time, since firms in each of the dirty, clean, and intermediate good sectors utilize sector-specific capital (and labour) for production, sectoral investment follows similar patterns: investment in the dirty energy sector declines while "green investment" increases.

Because our framework features financial frictions, the contractionary effects of fossil price shocks are amplified according to the usual financial accelerator logic. In line with Gertler and Karadi (2011), our setup introduces financial frictions in a standard way. Production in all sectors requires financing from banks to purchase the sector-specific capital input. As a result, firms issue shares to banks, in the form of equity. Banks collect liabilities in the form of deposits from households, and given a motivation for maturity transformation and subject to an (occasionally-binding) leverage constraint, attach a positive, sector-specific spread on their loans to firms. Since non-financial firms in the model require financing from banks for purchasing sector-specific capital, changes in asset prices as a result of changes in firm profitability impact bank balance sheets and amplify the effects on the real economy through a financial accelerator channel.

What happens as a results of an adverse fossil price shock? When dirty energy producers reduce their production of dirty energy inputs, prices of assets used to finance capital in the dirty energy sector decline. Analogously, the increase in the demand for clean energy production puts upward pressure on the price of clean energy assets. In equilibrium, the former effect dominates, lowering bank equity and consequently causing the leverage constraint of financial intermediaries to become binding. The tightening of leverage constraints contributes to increasing lending spreads across assets, and further amplifying the reduction in the demand for financing capital on behalf of non-financial firms. Overall, the banking sector generates a negative feedback loop, which further contracts investment and asset prices magnifying the effects of fossil price shocks.

In this disaggregated production economy with financial frictions, our analysis also focuses on the role of fiscal policy. In line with current policy practices, for example fiscal authorities in the EU27 have predominantly utilized untargeted price measures in the form of excise duties (or VAT changes) (see, e.g., Sgaravatti et al. (2023)), the fiscal policies employed to mitigate the inflationary consequence of fossil resource price shocks have taken the form of energy subsidies. In our model, we distinguish between subsidies to firms and subsidies to households (that is a subsidy to the production of energy, and a subsidy to its consumption). We also consider the case of a carbon subsidy (i.e. the inverse of a carbon tax), where the price of dirty energy used for production is directly targeted.

While all types of energy subsidies operate by aiming to reduce the price of energy, a nuanced insight from our frameworks is that the transmission on CPI and core inflation, as well as on aggregate output, differs meaningfully across subsidy types. This is a direct result of the differential sectoral effects that materialize in a disaggregated setup. Since each of the inputs which are subsidized are aggregated together with other factors of production using constant elasticity of substitution (CES) aggregators, each subsidy operates by affecting some combination of relative prices; however, the sets of relative prices affected each time, as well as the vertical position of each input in the production or consumption structure, produces different implications for the sign and magnitude of the responses of aggregate output and inflation rates.

Specifically, our analysis shows that an energy production subsidy can lower both core inflation and CPI inflation and increase aggregate output, while an energy consumption subsidy can only lower CPI inflation, while increasing core inflation and reducing aggregate output. In turn, a carbon subsidy lies in the middle, lowering both CPI and core inflation and increasing aggregate output, but less than an energy-production subsidy. Quantitatively, we find that the present value multiplier for the energy production subsidy converges to 1.7 in the long run, while the energy consumption subsidy produces a negative present value multiplier throughout the horizon and converging to -0.26 in the long run.

These differences arise due to a differential impact of subsidies on marginal costs of production and specifically on the post-subsidy energy price faced by households and firms. The energy production subsidy lowers the energy price faced by intermediate good producers resulting in a significant fall in their marginal costs. Lower marginal costs are subsequently passed through to final good firms resulting in a reduction in core inflation and CPI inflation. By contrast, an energy consumption subsidy lowers CPI inflation through its direct impact on the price of energy used for consumption, but in equilibrium, raises the demand for energy used for consumption. Dirty and clean energy producers then increase their production of energy to meet the additional demand, resulting in an increase of the post-subsidy price of energy faced by firms.

Finally, our framework delivers two insights in the context of carbon emissions: First, given that emissions are a byproduct of production in the dirty energy sector, as production of dirty energy responds following changes in energy-related subsidies, emissions simply respond accordingly. A carbon subsidy, which rewards the production of dirty energy by lowering its price, although balanced in terms of its impact on inflation and output, leads to the largest increase in carbon emissions relative to the case without subsidies. By contrast, energy consumption and production subsidies only modestly increases emissions, as they do not significantly affect the relative prices of dirty and clean energy inputs, utilized for the production of aggregate energy. Clearly, energy production subsidies are better suited to mitigate the contractionary effects of fossil price shocks in the medium term, while only modestly slowing down the transition to a low-carbon economy.

A second insight in the context of emissions is that a comprehensive set of macroprudential policies can be introduced to compensate for newly emerging transition risks. This possibility arises because energy subsidies contribute, albeit to different extents, towards temporarily slowing down the "green transition" when fossil prices increase. Our analysis shows that when the regulatory authority (the government in our setup) has access to macroprudential taxes and subsidies, which can be imposed on sectoral bank assets in bank portfolios, emission increases from energy subsidies can be mitigated. Specifically, a macroprudential tax on dirty energy assets in bank balance sheets tilts bank portfolios away from dirty energy assets and into assets used for the production of clean energy and the intermediate good. Given the large share of intermediate-goods capital in production, aggregate investment and output fall by less while emissions decline by more. Moreover, since the banking sector becomes less exposed to the dirty energy, bank equity drops by less, while "green investment" increases, highlighting the benefits of such an "emissions-prudential" policy.

Related literature

Our work is related to the still scarce literature assessing the implications of fiscal and monetary policy in mitigating increases in energy prices in DSGE model-based studies.

Papers closely related to ours are those that study the supply-side effect of energy price shocks. Baqaee and Farhi (2019), Baqaee and Farhi (2022) and Bachmann et al. (2022), find that rises in energy prices have a very limited effect on GDP, given realistic substitution elasticities. Kharroubi and Smets (2023) analyze how negative energy supply shocks can manifest as negative demand shocks, or a Keynesian supply shock. However, since these papers abstract from nominal rigidities, they do not feature a role for monetary policy. Instead, Bodenstein et al. (2011) and Pataracchia et al. (2023) incorporate a role for monetary policy through nominal rigidities.

More recently, Erceg et al. (2024), explore how energy subsidies can help address the consequences of energy price increases in closed and open economy models. Similar to us, they find that an energy consumption subsidy is less preferable, but in their analysis the mechanism hinges on the international nature of the policy (i.e. whether it is applied globally or in a closed economy). Our paper is complementary, but employs a granular setup of energy production, focusing on a framework with financial frictions that amplify effects of shocks and fiscal and macroprudential policies. Additionally, our analysis considers their impact on carbon emissions.

Much less vast, but closely related to our paper, is the literature featuring microeconomic heterogeneity and energy-related issues. Känzig (2023) and Auclert et al. (2023) study the macroeconomic effects of energy price shocks in energy-importing economies using a heterogeneous-agent New Keynesian model. While our paper focuses on similar questions it considers heterogeneity on the supply side of the economy combined with a banking sector.

Another stream of papers study climate mitigation policies in models with financial intermediaries (Benmir and Roman (2020); Diluiso et al. (2021); Nakov and Thomas (2023); Bartocci et al. (2022); Ferrari and Nispi-Landi (2022), among others). Relative to these works, our framework includes a role for disaggregated energy and a focus around the ability of fiscal and macroprudential policy instruments to mitigate the effects of energy price increases.

Finally, our work relates to the broader literature assessing the interaction between climate outcomes and the economy, which also feature an energy sector of different granularity into the framework. Golosov et al. (2014) is one of the first contributions to add fossil fuel (oil and coal) inputs in an otherwise standard DSGE model. For additional contributions, see e.g., Annicchiarico and Di Dio (2015), Airaudo et al. (2022), Varga et al. (2021), Coenen et al. (2023), among others. The focus of all these studies, relative to ours, however, lies on the impact of carbon taxation in affecting macroeconomic outcomes.

This paper consists of 5 sections. Section 2 describes the model in detail and presents the calibration. Section 3 presents quantitative analysis describing the propagation of a shock to the price of fossil resources. Section 4 explores the effectiveness of a set of energy subsidies, while section 5 illustrates how macroprudential policies can be utilized in parallel to energy subsidies to mitigate the increase in carbon emissions. Finally, section 6 concludes. An Appendix reports additional exercises and robustness checks.

2 Model

Our framework consists of a closed-economy New Keynesian model with financial intermediaries and disaggregated energy production and use.[3] On the demand side, households consume a composite final consumption good, which is composed of energy and a consumption good excluding energy. On the supply side, the intermediate good is produced by

[3]A schematic illustration of the model's structure can be seen in Figure 1.

monopolistically competitive firms using value added (a capital-labour bundle) and an energy composite aggregated in CES fashion. They then sell the intermediate good to perfectly competitive firms for private consumption, private investment and government consumption purchases.. The energy composite is produced by energy producers, who bundle clean and dirty energy inputs produced by monopolistically competitive dirty and clean energy producers, respectively. Each of the dirty and clean energy producers produce their inputs by combining sector-specific value added with natural resources (fossils vs. renewables).

An important feature of our model lies in the presence of financial frictions: Production in all sectors requires financing from banks to purchase the sector-specific capital input. As a result, firms issue shares to banks, in the form of equity. Banks collect liabilities in the form of deposits from households, and given a motivation for maturity transformation and subject to an (occasionally-binding) leverage constraint, attach a positive spreads on their loans to firms, which are also sector-specific.

On the policy side, the framework is closed as follows: The fiscal authority applies distortionary subsidies (taxes if positive) on the production and consumption of energy (at different levels, as shown below), which are financed by lump-sum transfers from households. The central bank implements a Taylor rule that features interest rate smoothing.

2.1 Households

There is a continuum of identical households of measure 1. Households consume a basket of energy and non-energy goods, work in each of the three sectors, and invest their savings into bank deposits and short-term government bonds. Labor is perfectly mobile across sectors.

In any period t, a fraction f of households are bankers and the remaining fraction $1-f$ are workers. Within the family, there is perfect consumption insurance. Workers supply labor to each sector and return their (after-tax) wage income to the household. Bankers manage financial intermediaries and also transfer their earnings back to the household. Households save by depositing funds into intermediaries they do not own.

Bankers have a finite lifetime. In every period a household stays a banker with probability σ and with probability $(1-\sigma)$ it remains a worker. Hence, in every period a fraction $(1-\sigma) f$ of households becomes a worker. Exiting bankers are replaced by the same number of (random) workers, keeping the relative shares of each household type fixed. Entering bankers are assigned with an amount of start-up funds.

The discounted utility of the household is given by

$$E_0 \sum_{i=0}^{\infty} \beta_t \left[\frac{(C_{t+1} - hC_{t+i-1})^{(1-\gamma)} - 1}{1-\gamma} - \frac{\chi}{1+\varphi} L_{t+i}^{1+\varphi} \right] \tag{1}$$

where E_0 is the expectation operator, $0 < \beta_t < 1$ is the (time-varying) discount rate, $0 < h < 1$, and $\gamma, \chi, \varphi > 0$. L_t is total labor supplied across the three value-added producing sectors, and C_t is a composite consumption good, which is produced by a competitive firm that bundles an energy consumption good, E_t^C, and a consumption good excluding energy, C_t^X using the CES aggregator:

$$C_t = \left[\omega_c^{\frac{1}{\epsilon_c}} \left(E_t^C\right)^{\frac{\epsilon_c - 1}{\epsilon_c}} + (1 - \omega_c)^{\frac{1}{\epsilon_c}} \left(C_t^X\right)^{\frac{\epsilon_c - 1}{\epsilon_c}}\right]^{\frac{\epsilon_c}{\epsilon_c - 1}} \tag{2}$$

where ω_c represents the share of energy in the composite consumption bundle and $\epsilon_c > 0$ is the elasticity of substitution between the two goods. As $\epsilon_c \to 0$, the two inputs are perfect complements, whereas if $\epsilon_c \to \infty$, they are perfect substitutes.

The demand equations for energy and the consumption good excluding energy are given by

$$E_t^C = \omega_c \left(\frac{\left(1 + \tau_t^{ec}\right) P_{E,t}}{P_{C,t}}\right)^{-\epsilon_c} C_t \tag{3}$$

$$C_t^X = (1 - \omega_c) \left(\frac{P_{C^X,t}}{P_{C,t}}\right)^{-\epsilon_g} C_t \tag{4}$$

where $P_{C,t}$ is the price of the final consumption good, and $P_{E,t}$ and $P_{C^X,t}$ are the prices of energy and the consumption good excluding energy, respectively. Finally, τ_t^{ec} is a distortionary subsidy (tax if positive) levied as a negative surcharge on the price of the energy good used for consumption.

Households save by holding perfectly substitutable deposits and short-term government bonds, both of which are one-period real assets paying the gross return R_t. The total quantity of short-term debt the household acquires is B_t^b. Households also receive real wage income $w_t = \frac{W_t}{P_t}$ by supplying labor to the intermediate good sector and the two energy-producing sectors.

The household budget constraint is

$$\left(1 + \tau_t^c\right) P_{C,t} C_t + B_t = w_t L_t + D_t + R_t B_{t-1}^b + T_t \tag{5}$$

where D_t are dividends, denoting the sum of payouts from the ownership of financial intermediaries and non-financial firms (including start-up funds), τ_t^c is VAT levied on the price of the consumption good, and T_t are lump-sum taxes (transfers if negative).

The household chooses C_t, L_t, B_t^b to maximize 1 subject to 5. The intertemporal Euler equation determining the (aggregate) consumption/saving decision, and the intratemporal condition determining optimal labor supply are:

$$E_t \Lambda_{t,t+1} R_{t+1} = 1 \tag{6}$$

$$w_t = \chi L_t^{\varphi} \mu_t^{-1} \tag{7}$$

with

$$\Lambda_{t,t+1} \equiv \beta_{t+1} \frac{\mu_{t+1}}{\mu_t} \tag{8}$$

and

$$\mu_t\left(1+\tau_t^c\right)P_{C,t}=(C_t-hC_{t-1})^{-\gamma}-\beta h(C_{t+1}-hC_t)^{-\gamma} \tag{9}$$

denoting the stochastic discount factor and marginal utility of consumption, respectively.

2.2 Production

There are six types of non-financial firms in the model: intermediate good producers, clean and dirty energy producers, capital goods producers, final good producers and final energy producers.

2.2.1 Intermediate goods producers

The intermediate good used for private consumption, H_t^C, private investement, H_t^I, and public consumption, H_t^G, are composites of differentiated intermediate-good varieties, $Y\left(j\right)_{m,t}$, which are produced by monopolistically competitive firms indexed by j. These firms combine value added, $KL\left(j\right)_{m,t}$, with an energy composite of energy used into production, $E\left(j\right)_t^Y$, using a CES technology. To simplify notation, in what follows we abstract from the firm-specific index j.

$$Y_{m,t}=\left[\omega_m^{\frac{1}{\epsilon_m}}\left(KL_{m,t}\right)^{\frac{\epsilon_m-1}{\epsilon_m}}+\left(1-\omega_m\right)^{\frac{1}{\epsilon_m}}\left(E_t^Y\right)^{\frac{\epsilon_m-1}{\epsilon_m}}\right]^{\frac{\epsilon_m}{\epsilon_m-1}} \tag{10}$$

where ω_m represents the share of value added in the production of the intermediate good, and $\epsilon_m>0$ is the elasticity of substitution between value added (in the intermediate good production sector) and the energy composite. The demand for the energy good by intermediate good producers is given by

$$E_t^Y=P_{m,t}^{\epsilon_m}\left(1-\omega_m\right)Y_{m,t}\left(\left(1+\tau_t^{ey}\right)P_{E,t}\right)^{-\epsilon_m} \tag{11}$$

where$P_{E,t}$ denotes the price of the energy good, and τ_t^{ey} is a subsidy (tax if positive) levied as a negative surcharge on the price of aggregate energy demanded by producers. In contrast to τ_t^{ec}, this subsidy operates on the supply side.

In turn, production of value added is possible with a constant returns to scale technology, combining sector-specific capital, $K_{m,t}$ and labor, $L_{m,t}$ inputs:

$$KL_{m,t}=\left(K_{m,t-1}\right)^{\alpha_m}\left(L_{m,t}\right)^{1-\alpha_m} \tag{12}$$

The demand for labor in the production of the intermediate good is given by

$$w_tL_{m,t}=\left(1-\alpha_m\right)MC_{m,t}\left(\omega_mY_{m,t}\right)^{\frac{1}{\epsilon_m}}\left(KL_{m,t}\right)^{\frac{\epsilon_m-1}{\epsilon_m}} \tag{13}$$

whereas the demand for capital is

$$K_{m,t} = \omega_m \alpha_m \left(\frac{Z_t}{MC_{KL,t}} \right)^{-1} \left(\frac{MC_{KL,t}}{MC_{m,t}} \right)^{-\epsilon_m} Y_{m,t} \tag{14}$$

with $MC_{m,t}$ denoting the marginal cost associated with producing a unit of intermediate good, $MC_{KL,t}$ the marginal cost associated with producing a unit of value added in the intermediate good sector, and $Z_{m,t}$ gross profits per unit of capital:

$$MC_{m,t} = \left[\omega_m \left(MC_{KL,t} \right)^{1-\epsilon_m} + (1-\omega_m) \left(\left(1+\tau_t^{ey} \right) P_{E,t} \right)^{1-\epsilon_m} \right]^{\frac{1}{1-\epsilon_m}} \tag{15}$$

$$MC_{KL,t} = \frac{1}{\alpha_m^{\alpha_m} \left(1-\alpha_m \right)^{1-\alpha_m} Z_t^{\alpha_m} w_t^{1-\alpha_m}} \tag{16}$$

$$Z_t K_{m,t} = \alpha_m MC_{m,t} \left(\omega_m Y_{m,t} \right)^{\frac{1}{\epsilon_m}} \left(KL_{m,t} \right)^{\frac{\epsilon_m - 1}{\epsilon_m}} \tag{17}$$

Intermediate good producers are monopolistically competitive, setting their prices in a staggered manner as in Calvo (1983) with backward-looking indexation. In each period, an intermediate good firm is able to adjust its price with probability $1-\psi_m$. Accordingly, each firm chooses the reset price $P_{m,t}^*$ to maximize expected discounted profits subject to the restriction on the adjustment frequency. The first order condition following price optimisation is given by

$$E_t \sum_{j=0}^{\infty} \psi^j \Lambda_{t,t+j} \left[\frac{P_{m,t}^*}{P_{m,t+j}} - \varsigma_m P_{m,t+j} \right] Y_{m,t+i}(i) = 0 \tag{18}$$

where $\Lambda_{t,t+j}$ represents the stochastic discount factor and $\varsigma_m = \frac{\zeta_m}{\zeta_m - 1}$ is the markup. Following from the law of large numbers, the relation for the evolution of the core price level excluding energy is

$$P_{m,t} = \left[(1-\psi_m) \left(P_{m,t}^* \right)^{1-\zeta_m} + \psi_m \left(P_{m,t-1} \right)^{1-\zeta_m} \right]^{\frac{1}{1-\zeta_m}} \tag{19}$$

2.2.2 Energy producers

Perfectly competitive energy producers produce the energy composite, E_t, by combining clean, $E_{g,t}$, and dirty, $E_{f,t}$, energy inputs using a CES technology

$$E_t = \left[\omega_e^{\frac{1}{\epsilon_e}} E_{g,t}^{\frac{\epsilon_e - 1}{\epsilon_e}} + (1-\omega_e)^{\frac{1}{\epsilon_e}} E_{f,t}^{\frac{\epsilon_e - 1}{\epsilon_e}} \right]^{\frac{\epsilon_e}{\epsilon_e - 1}} \tag{20}$$

where ω_e represents the share of clean energy in the production of energy and $\epsilon_e > 0$ is the elasticity of substitution between clean and dirty energy inputs.

Letting $P_{E_g,t}$ and $P_{E_f,t}$ be the price of clean and dirty energy, respectively, the price of energy is given by

$$P_{E,t} = \left[\omega_e P_{E_g,t}^{1-\epsilon_e} + (1-\omega_e)\left(\left(1+\tau_t^D\right) P_{E_f,t}\right)^{1-\epsilon_e}\right]^{\frac{1}{1-\epsilon_e}} \tag{21}$$

where the price of dirty energy used in production is also subject to a subsidy, τ_t^D. Note that τ_t^D can be interpreted as a carbon subsidy in our model, as in similar frameworks of energy-generation (see, e.g., Coenen et al. (2023) which analyze the role of carbon taxation).

The demand for clean and dirty energy is given by:

$$E_{g,t} = \omega_g E_t \left(\frac{P_{E_g,t}}{P_{E,t}}\right)^{-\epsilon_g} \tag{22}$$

$$E_{f,t} = (1-\omega_g)\, E_t \left(\frac{\left(1+\tau_t^D\right) P_{E_f,t}}{P_{E,t}}\right)^{-\epsilon_g} \tag{23}$$

Carbon emissions Finally, carbon emissions are released into the environment as a by-product of production in the dirty energy sector, which utilizes in turn both a fossil resource and a sector-specific capital-labour bundle, as we explain below:

$$M_{f,t} = \varpi E_{f,t} \tag{24}$$

where ϖ measures the carbon intensity, that is the share of emissions produced by the production of one unit of dirty energy.

2.2.3 Clean and dirty energy producers

Clean and dirty energy inputs are themselves composites of sector-specific value added and a natural resource, produced by monopolistically competitive clean and dirty energy producers. The dirty energy producer, produces dirty energy, $E_{f,t}$ using sector-specific value added, $KL_{f,t}$, and a natural resource, $\mathcal{F}_t$, interpreted as fossil fuels, using a CES technology

$$E_{f,t} = \left[\omega_f^{\frac{1}{\epsilon_f}} KL_{f,t}^{\frac{\epsilon_f-1}{\epsilon_f}} + (1-\omega_f)^{\frac{1}{\epsilon_f}} \mathcal{F}_t^{\frac{\epsilon_f-1}{\epsilon_f}}\right]^{\frac{\epsilon_f}{\epsilon_f-1}} \tag{25}$$

Similarly, the clean energy producer, produces clean energy, $E_{g,t}$ using sector-specific value added, $KL_{g,t}$, and a natural resource, $\mathcal{G}_t$, interpreted as renewable resources, using the CES technology

$$E_{g,t} = \left[\omega_g^{\frac{1}{\epsilon_g}} KL_{g,t}^{\frac{\epsilon_g-1}{\epsilon_g}} + (1-\omega_g)^{\frac{1}{\epsilon_g}} \mathcal{G}_t^{\frac{\epsilon_g-1}{\epsilon_g}}\right]^{\frac{\epsilon_g}{\epsilon_g-1}} \tag{26}$$

where ω_f, ω_g represent the shares of value added in the production of clean and dirty energy, respectively and $\epsilon_f,\epsilon_g > 0$ are the elasticities of substitution between value added and the fossil or renewable resource.

In turn, value added in each energy sector is produced using the constant returns to scale technologies

$$KL_{f,t} = (K_{f,t-1})^{\alpha_f} (L_{f,t})^{1-\alpha_f} \tag{27}$$

$$KL_{g,t} = (K_{g,t-1})^{\alpha_g} (L_{g,t})^{1-\alpha_g} \tag{28}$$

Demand for labor in the production of each energy good is given by

$$w_t L_{f,t} = (1-\alpha_f) MC_{E_f,t} (\omega_f E_{f,t})^{\frac{1}{\epsilon_f}} (KL_{f,t})^{\frac{\epsilon_f - 1}{\epsilon_f}} \tag{29}$$

$$w_t L_{g,t} = (1-\alpha_g) MC_{E_g,t} (\omega_g E_{g,t})^{\frac{1}{\epsilon_g}} (KL_{g,t})^{\frac{\epsilon_g - 1}{\epsilon_g}} \tag{30}$$

with $MC_{E_f,t}$ and $MC_{E_g,t}$ analogously defined to the marginal cost of intermediate goods producers (equation 15). It follows that gross profits per unit of capital in each energy sector can be expressed as

$$Z_{f,t} K_{f,t} = \alpha_f MC_{E_f,t} (\omega_f E_{f,t})^{\frac{1}{\epsilon_f}} (KL_{f,t})^{\frac{\epsilon_f - 1}{\epsilon_f}} \tag{31}$$

$$Z_{g,t} K_{g,t} = \alpha_g MC_{E_g,t} (\omega_g E_{g,t})^{\frac{1}{\epsilon_g}} (KL_{g,t})^{\frac{\epsilon_g - 1}{\epsilon_g}} \tag{32}$$

As in the case of intermediate good producers, dirty and clean energy firms also set their prices as in Calvo (1983) with backward-looking indexation and sector-specific markups, giving rise to the following relations for the evolution of the clean and dirty energy price levels, which are analogous to equation 19.

$$P_{E_f,t} = \left[(1-\psi_f) \left(P^*_{E_f,t} \right)^{1-\zeta_f} + \psi_f \left(P_{E_f,t-1} \right)^{1-\zeta_f} \right]^{\frac{1}{1-\epsilon_f}} \tag{33}$$

$$P_{E_g,t} = \left[(1-\psi_g) \left(P^*_{E_g,t} \right)^{1-\zeta_g} + \psi_g \left(P_{E_g,t-1} \right)^{1-\zeta_g} \right]^{\frac{1}{1-\zeta_g}} \tag{34}$$

2.2.4 Supply of natural resources

We assume that fossil and green resources are a fixed endowment, and that the price of each resource adjusts instantaneously to meet aggregate demand, hence: $\mathcal{F}_t = \overline{\mathcal{F}}$ and $\mathcal{G}_t = \overline{\mathcal{G}}$. Letting $P_{\mathcal{F},t}$ and $P_{\mathcal{G},t}$ denote the price of the fossil and renewable resource, respectively, then the demand for each resource is given by

$$\mathcal{F}_t = (1-\omega_{f,t}) E_{f,t} \left(\frac{P_{\mathcal{F},t}}{P_{E_f,t}} \right)^{-\epsilon_f} \tag{35}$$

$$\mathcal{G}_t = (1-\omega_{g,t}) E_{g,t} \left(\frac{P_{\mathcal{G},t}}{P_{E_g,t}} \right)^{-\epsilon_g} \tag{36}$$

2.2.5 Capital goods producers

Capital is produced by perfectly competitive capital producers, which use final goods as an input and are subject to adjustment costs. They sell the new capital to firms in sector $s \in \{m, f, g\}$ at the price $Q_{s,t}$. Given that households own capital producers, the objective of the capital producer is to choose investment, $I_{s,t}$ to maximize profits. The latter arise only outside the steady state and are redistributed lump-sum to households:

$$\max E_t \sum_{\tau=t}^{\infty} \Lambda_{t,\tau} \left\{ Q_{s,\tau}^{i} I_{\tau} - \left[1 + f\left(\frac{I_{s,\tau}}{I_{s,\tau-1}} \right) I_{s,\tau} \right] \right\} \tag{37}$$

The solution to the profit maximization problem then implies that the price of capital goods is equal to the marginal cost of investment goods production:

$$Q_{s,t} = 1 + f\left(\frac{I_{s,t}}{I_{s,t-1}}\right) + \frac{I_{s,t}}{I_{s,t-1}} f'\left(\frac{I_{s,t}}{I_{s,t-1}}\right) - E_t \Lambda_{t,t+1} \left(\frac{I_{s,t+1}}{I_{s,t}}\right)^2 f'\left(\frac{I_{s,t+1}}{I_{s,t}}\right) \tag{38}$$

The acquisition of capital by intermediate goods producers and dirty and clean energy producers works as follows. At the end of period t, each firm is left with a capital stock $(1-\delta_s) K_{s,t}$. It then buys $I_{s,t}$ units of new capital from capital producers, so its capital stock in period $t+1$ is given by

$$K_{s,t+1} = (1-\delta_s) K_{s,t} + I_{s,t} \tag{39}$$

To finance new capital, the firm must obtain funding from a financial intermediary. For each new unit of capital acquired, it issues a state-contingent claim to the future stream of earnings from the unit. Given perfect competition, the value of this security $Q_{s,t}$ equals the market price of the capital underlying the security. The period $t+1$ payoff is given by $Z_{s,t+1} = (1-\delta_s) Q_{s,t+1}$, which denotes the sum of gross profits and the value of the leftover capital. In turn, $Z_{s,t}$ for each sector $s \in \{m, f, g\}$ correspond to the rates of return in equations 17, 31, and 32.

2.2.6 Final good producers

Representative firms produce the final private consumption good, H_t^C, private investement good, H_t^I, and public consumption good, H_t^G using a constant elasticity of substitution composite produced by the mass one of differentiated intermediate good producers

$$H_t^C = \left(\int_0^1 H(j)_t^{C\,\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon-1}{\epsilon}} \tag{40}$$

$$H_t^I = \left(\int_0^1 H(j)_t^{I\,\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon-1}{\epsilon}} \tag{41}$$

$$H_t^G = \left(\int_0^1 H\left(j\right)_t^{G\ \frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon-1}{\epsilon}} \tag{42}$$

Aggregating across the three final-goods, the demand for intermediate goods j is hence

$$H\left(j\right)_t = H\left(j\right)_t^C + H\left(j\right)_t^I + H\left(j\right)_t^G = \left(\frac{P\left(j\right)_{m,t}}{P_{m,t}} \right)^{-\epsilon} \left(H_t^C + H_t^I + H_t^G \right)$$

with $P_{m,t} = \left(\int_0^1 P\left(j\right)_{m,t}^{\ \frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon-1}{\epsilon}}$.

2.3 Banks

Banks collect short-term deposits from households and use them, together with equity capital to purchase corporate and government bonds. Corporate bonds provide funding for non-financial firms in each of the three production sectors to finance their capital acquisitions and are interpreted as equity. For each sector $s \in \{m, f, g\}$, the rate of return on the security $R_{s,t+1}$ is given by

$$R_{s,t+1} = \frac{Z_{s,t+1} + \left(1 - \delta_s\right) Q_{s,t+1}}{Q_{s,t}} \tag{43}$$

Let N_t be the amount of net worth (equity capital) that a banker has at the end of period t, B_t^b the deposits received from households, and $S_{s,t}^b$ the quantity of financial claims on non-financial firms that the bank holds. The intermediary's balance sheet is then given by

$$Q_{m,t}S_{m,t}^b + Q_{f,t}S_{f,t}^b + Q_{g,t}S_{g,t}^b = N_t + B_t^b \tag{44}$$

Net worth accumulates from retained earnings and is therefore given by the difference between earnings on assets (firm securities) and interest payments on liabilities (household deposits)

$$N_{t+1} = R_{m,t+1}Q_{m,t}S_{m,t}^b + R_{f,t+1}Q_{f,t}S_{f,t}^b + R_{g,t+1}Q_{g,t}S_{g,t}^b - R_{t+1}B_t^b \tag{45}$$

From 44 and 45, the evolution of net worth can be expressed as

$$N_{t+1} = \left(R_{m,t+1} - R_{t+1}\right) Q_{m,t}S_{m,t}^b + \left(R_{f,t+1} - R_{t+1}\right) Q_{f,t}S_{f,t}^b + \left(R_{g,t+1} - R_{t+1}\right) Q_{g,t}S_{g,t}^b + R_{t+1}N_t \tag{46}$$

The banker's objective is to maximize the discounted stream of payouts back to the household, or differently, its terminal wealth until it exits the industry. If $V_t\left(N_t\right)$ denotes the end-of-period value function then the banker maximizes

$$V_t\left(N_t\right) = \max_{\{S_{s,t+1}\}} E_t \Lambda_{t,t+1} \left[\left(1 - \sigma\right) N_{t+1} + \sigma V_{t+1}\left(N_t\right) \right] \tag{47}$$

To motivate a limit on the bank's ability to obtain deposits, banks face a moral hazard problem, in which at the beginning of the period the banker can choose to divert a fraction

θ of funds from the assets it holds and transfer the proceeds back to the household. Hence for depositors to be willing to lend to bankers, the value of the bank, $V_t(N_t)$, must not be lower than the fraction of divertible funds:

$$V_t(N_t) \geq \theta \left(Q_{m,t} S^b_{m,t} + \Psi_f Q_{f,t} S^b_{f,t} + \Psi_g Q_{g,t} S^b_{g,t} \right) \tag{48}$$

where Ψ_g, Ψ_f are sectoral absconding rates. The different absconding rates on firm assets give rise to imperfect substitutablity between these securities in the bank's balance sheet and therefore to limited arbitrage. An additional consequence is that risk premia become sector-specific and increase proportionately to sectoral absconding rates.

The banker's maximization problem is to choose its portfolio of $S^b_{s,t}$ to maximize 47 subject to 68. By substituting inside V_t equations 46 and 47, the Lagrangean of the problem can be expressed as

$$\begin{aligned} \mathcal{L} \; = E_t \Big\{ & \Lambda_{t,t+1} (1-\sigma) \Big[(R_{m,t+1} - R_{t+1}) Q_{m,t} S^b_{m,t} + (R_{f,t+1} - R_{t+1}) Q_{f,t} S^b_{f,t} \\ & + (R_{g,t+1} - R_{t+1}) Q_{g,t} S^b_{g,t} + N_t (R_{t+1}) \Big] + \sigma V_{t+1}(N_{t+1}) \Big\} \\ & + \lambda_t \left[V_t(N_t) - \theta \left(Q_{m,t} S^b_{m,t} + \Psi_f Q_{f,t} S^b_{f,t} + \Psi_g Q_{g,t} S^b_{g,t} \right) \right] \end{aligned} \tag{49}$$

As is standard in these models, to solve the banker's problem we postulate that the value function is linear in net worth, so that $V_t = \upsilon_t N_t$. Defining $\Omega_{t+1} = 1 - \sigma + \sigma \nu_{t+1}$, the FOCs of this problem are given by

$$\frac{\partial L}{\partial S_{m,t}} : \qquad E_t \Lambda_{t,t+1} \Omega_{t+1} (R_{m,t+1} - R_{t+1}) = \lambda_t \theta \tag{50}$$

$$\frac{\partial L}{\partial S_{g,t}} : \qquad E_t \Lambda_{t,t+1} \Omega_{t+1} (R_{g,t+1} - R_{t+1}) = \lambda_t \theta \Psi_g \tag{51}$$

$$\frac{\partial L}{\partial S_{f,t}} : \qquad E_t \Lambda_{t,t+1} \Omega_{t+1} (R_{f,t+1} - R_{t+1}) = \lambda_t \theta \Psi_f \tag{52}$$

We assume that the incentive constraint is always binding, so that $\lambda_t > 0$ and positive excess returns emerge in equilibrium. If instead $\lambda_t = 0$ then financial markets would be frictionless. This incentive constraint in turn places a constraint on the bank's leverage ratio, ϕ_t, which defines the bank's portfolio as a share of its net worth:

$$\phi_t = \frac{Q_{m,t} S^b_{m,t} + \Psi_f Q_{f,t} S^b_{f,t} + \Psi_g Q_{g,t} S^b_{g,t}}{N_t} \tag{53}$$

which by substituting equation 68 can be expressed as

$$\phi_t = \frac{\upsilon_t}{\theta} \tag{54}$$

The share of dirty energy securities that enter the bank's balance sheet constraint are weighted by the sectoral absconding rates and as such burden the banks' balance sheet capacity by more than intermediate good or clean energy assets.

Substituting 54 into 50 and using the envelope condition of problem 49, which is given by $E_t \Lambda_{t,t+1} \Omega_{t+1} R_{t+1} = \upsilon_t - \theta \upsilon_t$, we can obtain an expression for the marginal value of net worth as given by

$$\upsilon_t = \frac{\theta E_t \Lambda_{t,t+1} \Omega_{t+1} R_{t+1}}{\theta - E_t \Lambda_{t,t+1} \left(R_{m,t+1} - R_{t+1}\right)} \tag{55}$$

Finally, total net worth evolves as the sum of retained earnings of surviving bankers, N_t^o, and new bankers, N_t^y:

$$N_t = N_t^o + N_t^y \tag{56}$$

where funds of new bankers are the transfers received by exiting bankers and correspond to $\frac{\kappa}{1-\sigma}$ of total assets. Therefore, the evolution of net worth of surviving and new bankers is given by:

$$\begin{aligned} N_t^o = \chi \Big[& \left(R_{m,t} - R_t\right) Q_{m,t-1} S^b_{m,t-1} + \left(R_{f,t} - R_t\right) Q_{f,t-1} S^b_{f,t-1} \\ & + \left(R_{g,t} - R_t\right) Q_{g,t-1} S^b_{g,t-1} + R_t \Big] N_{t-1} \end{aligned} \tag{57}$$

and

$$N_t^y = \kappa \left(Q_{m,t} S^b_{m,t-1} + Q_{f,t} S^b_{f,t-1} + Q_{g,t} S^b_{g,t-1}\right) \tag{58}$$

2.4 Monetary policy

Conventional monetary policy follows from a Taylor-type rule targeting variations in core inflation (i.e. inflation excluding energy) and output relative to their steady state levels:

$$\frac{i_t}{i_{t-1}} = \left(\frac{i_t}{i_{t-1}}\right)^{\kappa_i} \left[\left(\frac{\pi_{m,t}}{\bar{\pi_m}}\right)^{\kappa_\pi} \left(\frac{Y_t}{\bar{Y}}\right)^{\kappa_y} \right]^{1-\kappa_i} \tag{59}$$

where $\kappa_i > 0$ is an interest rate smoothing parameter, $\kappa_\pi > 0$ is the weight on variations in core inflation, and $\kappa_y > 0$ the weight attached to variations in output.

2.5 Fiscal policy

Revenues of the government consist of new issuance of government debt, receipts from the different energy-related taxes, lump-sum taxes, and transfers from the central bank, z_t. Together they finance expenditures on government consumption, which are assumed to be a constant share of output, $G_t = \bar{g} Y_t$, and interest payments on debt.

The (consolidated) government budget constraint is then given by

$$P_t^G G_t - T_t = \sum_s \left(R_{s,t} - R_t\right) B^p_{t-1} + \tau_t^{ec} P_{E,t} E_t^C + \tau_t^c P_{C,t} C_t + \tau_t^{ey} P_{E,t} E_t^Y + \tau_t^D P_{E_f,t} E_t^f \tag{60}$$

2.6 Aggregation

For sector $s \in \{m, f, g\}$, market clearing in the market for private securities requires that their supply at the end of period t is equal to the sum of leftover capital and newly acquired capital:

$$\sum_s S_{s,t} = \sum_s (1 - \delta_s) K_{s,t} \tag{61}$$

and that total securities are equal to the sum of securities purchased by the central bank and those held by banks:

$$\sum_s S_{s,t} = \sum_s S^b_{s.t} + \sum_s S^p_{s.t} \tag{62}$$

In the market for energy, aggregate energy supplied is the sum of energy demanded by intermediate good firms and households:

$$E_t = E^Y_t + E^C_t \tag{63}$$

Market clearing in the government bond market requires that the supply of deposits is equal to the issuance of riskless short-term debt, which is kept fixed following from the assumption of the consolidated government running a balanced budget in every period:

$$B^b_t + B^p_t = B_t = \bar{B} \tag{64}$$

Labor market clearing requires that labor supply equals labor demand:

$$L_t = \sum_s L_{s,t} \tag{65}$$

Finally, the (real) resource constraint of the economy is given by

$$Y_t = C_t + G_t + \left[1 + \sum_s f\left(\frac{I_{s,t}}{I_{s,t-1}}\right)\right] I_{s,t} + \Xi_t \tag{66}$$

2.7 Calibration

Parameter values are shown in Table 1. The bulk of the parameters are based on Coenen et al. (2018), and are partly calibrated and partly estimated on EA data using standard Bayesian methods.

The steady state shares of different energy components are obtained from the OECD, KLEMS, and Eurostat databases. The steady-state share of energy in consumption is 5.5% of GDP. The steady-state share of energy in production is 7.2% of GDP. The share of clean energy in total energy is 29.3%. The largest component in the production and imports of clean energy in the euro area is renewables, whereas for dirty energy it consists of oil, coal, and gas. The share of fossil/green resources in the production of value added in each energy sector is 73%.

Regarding the energy-related structural parameters, the analysis calibrates the elasticities of substitution using evidence from the literature.[4] Following Bodenstein et al. (2011) and Coenen et al. (2023), the energy consumption good and the consumption good excluding energy are imperfect complements, with elasticity of substitution, ϵ_c, set at 0.4. Similarly, the substitution elasticity between the energy composite and value added in each of the intermediate good, ϵ_m, dirty energy, ϵ_f, and clean energy sectors, ϵ_g, is set to 0.4, also implying imperfect complementarity. In turn, we set the substitution elasticity between dirty and clean energy, ϵ_e, in aggregate energy production to 1.8 following Papageorgiou et al. (2017) who estimate CES production functions of dirty and clean energy inputs for a panel of 26 countries using sectoral data. A value of $\epsilon_e > 1$ implies that clean and dirty energy bundles are (imperfect) substitutes rather than complements, and this specification is also consistent with Acemoglu et al. (2012) and Varga et al. (2021).[5]

Finally, the remaining financial parameters are calibrated following Karadi and Nakov (2020), and the Taylor rule is calibrated according to Coenen et al. (2023).

3 Fossil Price Shocks and Financial Frictions

Our analysis first traces out the impact of an increase in the price of fossil resources on aggregate macroeconomic variables as well as its differential effects across the dirty and clean energy sectors. Our analysis then shows that the presence of financial frictions amplifies the shock's propagation through the banking sector.

3.1 Fossil resource price increase

Global commodity price increased by more than 100% during the 2021-2022 period. Against the backdrop of this experience, our analysis illustrates the channels at work in our model by considering a one-period increase in the fossil resource price of 50% with persistence equal to 0.85. This benchmark also allows for a comparison with similar studies in the literature: for example, Coenen et al. (2023) assume a 20% permanent increase in the price of fossil resources while using an estimated model of the euro area; Pataracchia et al. (2023) assume a 10 USD increase in the Brent oil price with estimated persistence of 0.85. The dynamics in the price of the fossil resource for our exercise are depicted in the left panel of Figure 2, and remain unchanged for the remainder of the paper.

At the aggregate level, the increase in the fossil energy price leads to higher headline and core inflation, and lower output. On the nominal side, as energy is directly used in consumption, the increase in the fossil resource price feeds directly through to the price of

[4] In the Appendix, we perform sensitivity on the elasticities of substitution across different energy sources.

[5] These substitution elasticities combined with the steady state shares imply the quasi-shares reported in Table 1, namely $\omega_m, \omega_c, \omega_g$ and ω_f.

the final consumption good.CPI headline inflation increases by around 1.3 p.p. Dirty energy producers, which utilize fossil resources for production of the dirty energy input, experience an increase in their marginal costs, which they pass on to producers of the intermediate good, and thereafter to the final-good producers. Overall, core inflation increases by around 0.6 p.p. On the real side, the fall in current and expected future real income of households causes them to cut back on consumption, while non-financial firms experience a fall in their current and expected future profitability, causing them to cut back on investment. Overall, the decline in aggregate demand contributes to lowering GDP by around 1.2% in the short term. Figure 3 displays the associated dynamics.

At the sectoral level, substitution away from dirty to clean energy takes place, mitigating aggregate energy quantity and price effects. Following an increase in the price of dirty energy, aggregate energy providers substitute away from utilizing more costly dirty energy and into utilizing less costly clean energy for the production of the aggregate energy good used in intermediate good production. The increased demand for clean energy places upward pressure on the price of the clean energy input. Due to imperfect substitutability across energy inputs, in equilibrium, the effect from the fall in dirty energy dominates, implying a reduction in aggregate energy and an increase in the aggregate energy price by around 15%. This negative supply shock and the associated substitution effects are captured by the right panel of Figure 2 while Figure 3 captures the substitution dynamics.

In our setup, firms in each of the dirty, clean, and intermediate good sectors, utilize sector-specific sector-specific capital (and labour) for production. As a result, sectoral investment sectoral patterns in line with the sectoral relative price effects: investment in the dirty energy sector declines while investment in the clean energy sector increases. Given the sector-specific nature of capital and investment goods in our model, a fossil price shock therefore contributes to endogenously incentivizing "green investment." However, investment in the intermediate good sector, which represents the majority of investment in the economy, declines following from the reduced demand and higher price of aggregate energy.

The financial sector contributes to an amplification of the real effects of fossil price shocks through a classic financial accelerator mechanism. In the steady state of the model—before the fossil price shock materializes—the leverage constraint of banks is slack. As dirty energy producers reduce their production of dirty energy inputs, prices of assets used to finance capital in the dirty energy sector decline. Analogously, the increase in the demand for clean energy production puts upward pressure on the price of clean energy assets. However, in line with movements in real allocations across energy sectors, the overall effect on bank equity is negative. The latter is largely due to the reduction in asset prices of intermediate good producers, which demand less capital services for intermediate good production, following from the increase in the aggregate energy price. The fall in bank equity causes the leverage constraint of financial intermediaries to become binding, forcing them to further restrict lending to non-financial firms across the dirty energy and intermediate good sectors. The tightening of leverage constraints contributes to increasing lending spreads across assets, amplifying the reduction in the demand for financing capital on behalf of non-financial firms. By contrast, in a model without financial frictions, the economy would experience a milder contraction following a fossil price increase. Figure 6 illustrates this difference. Without leverage constraints, lending premia faced by non-financial firms are absent, mitigating the reduction in production. At the sectoral level, in a model without financial frictions, the economy moves more strongly towards the production of clean energy, while investment in the intermediate good sector declines by less. Instead, the response of dirty energy production across an economy with and without financial frictions is more similar (and carbon emissions as a byproduct). This result follows from the exgenous impact of fossil price shock on the dirty energy sector.

A further model exercise traces out the effect of a fossil price shock when absconding rates differ across energy assets. Motivation for such an exercise includes the systematic market risk associated with brown assets, such as carbon pricing, regulation, reputational concerns, asset stranding and climate hedging risks. Moreover, the recent high demand for green assets from Environmental, Social, and Governance (ESG) investors lowers the expected returns of green assets (see, e.g., Bolton and Kacperczyk (2021); Pastor et al. (2021); Pedersen et al. (2021).) The exercise sets $\Psi_f = 1.5, \Psi_g = 1$ implying that dirty energy assets command a higher risk premium in the steady state. A lower relative riskiness of clean energy assets allows clean investment to expand by more by limiting the increase in the associated lending rate following the fossil price shock. Figure 6 illustrates this finding with the dashed blue IRFs.

4 Energy Subsidies

We are interested in understanding the propagation mechanism of different energy-related fiscal policies on the macroeconomy and on carbon emissions, in particular in mitigating the inflationary consequences of fossil resource price increases, recognizing that such schemes may temporarily adversely affect carbon emissions.

The fiscal policies chosen are motivated following Sgaravatti et al. (2023), who document the implemented fiscal responses across EU27 countries designed to shield households from the consequences of the energy crisis materializing over September 2021 to January 2023 in the EA. Out of the various fiscal instruments available, around 60% of funding in the EU27 (ca. Eur 220,000 million) was allocated towards untargeted price measures, such as cuts to excise duties and VAT. In our model, we capture untargeted price measures through the aggregate energy subsidy and distinguish between subsidies to firms and subsidies to households (that is a subsidy to the production of energy, and a subsidy to its consumption). We also consider the case of a carbon subsidy (i.e. the inverse of a carbon tax), where the production of dirty energy is subsidized. We deem the latter relevant given the still fossil-intensive nature of production in the EA. For illustration, we also compare the transmission channels of each subsidy relative to a VAT decrease, whose properties are familiar. In terms of results, we report impulse response functions in deviations from the exogenous fossil price increase, and fiscal and emission multipliers.

4.1 Inspecting energy-related fiscal policies

The experiments are designed in the following manner. We first calculate the share of revenues (as a % of GDP) that arise from each subsidy in the steady state. We then separately increase the associated subsidy rate, from its steady state value in order to generate an (ex-ante) decrease in government revenues by 1% on impact, which are subsequently redistributed to households in a lump-sum fashion.[6]. From period 1 onwards, each subsidy follows an AR(1) process, with autoregressive coefficient of 0.85, equal to that of the fossil resource price shock.

Figures 7 and 8 presents the impulse responses of different energy subsidies when combined with a shock to the fossil resource price. The solid black lines represent the case of no subsidies. Relative to the fossil price shock, overall, the results illustrate how an energy production subsidy can lower both core inflation (i.e. inflation excluding energy) and CPI inflation and increase aggregate output, while an energy consumption subsidy can only lower CPI inflation, but increase core inflation and reduce aggregate output. In turn, a carbon subsidy, lies in the middle, lowering both CPI and core inflation and increasing aggregate output, but to less of an extent relative to the energy production subsidy.

Energy production subsidies An energy production subsidy (dashed green lines) consists of a negative surcharge on the price of aggregate energy utilized by intermediate good firms for production of the intermediate good. This subsidy directly lowers the after-subsidy energy price faced by producers resulting in a significant fall in their marginal costs. Lower marginal costs are subsequently passed over to final good firms resulting in a reduction in core inflation relative to the fossil price increase.

To see this more clearly, marginal costs are a CES aggregate of the after-subsidy energy price and the contribution from wages and the return to capital in the intermediate good sector. In equilibrium, the lower after-subsidy energy price raises the production of energy, and given the complementarity of energy with value added in the intermediate good sector, also increases capital and labour demand, pushing up the real wage and the return from sector-specific capital. In equilibrium however, and given the imperfect complementarity with the energy price, their contribution towards marginal costs of intermediate good firms does not compensate for the decrease arising from the fall in after-subsidy energy prices.

On the real side, given the fall in marginal costs, energy production is increased, allowing for an increase in investment, consumption and hence GDP. On the financial side, the

[6]This specification implies that the fiscal authority runs a balanced budget, allowing to circumvent the confounding of the analysis from any effects related to financing decisions of the government

increased demand for capital across sectors, pushes up asset prices, relaxing bank balance sheet constraints, and allowing additional financing to be extended to non-financial firms for investment.

Energy consumption subsidies Next, we evaluate the impact of a subsidy to the price of energy consumed by households (dashed blue lines). The main difference to the energy production subsidy is that the energy consumption subsidy does not contribute towards reducing marginal costs of intermediate good firms. Instead, in equilibrium, as the consumption subsidy increases the demand for energy used for consumption, the (after-subsidy) price of energy faced by firms rises, contributing modestly, but still visibly, to an increase in marginal costs, and hence core inflation. Instead, CPI inflation declines on impact following from the (mechanical) reduction in the post-subsidy energy price included in the aggregate consumption bundle. Notably, in the medium term, CPI inflation remains persistently above the case of no subsidies (black solid lines) as the subsidy decays, but the demand for energy consumption remains elevated.

On the real side, faced with higher energy prices, intermediate good firms (marginally) reduce their use of energy for production and consequently also their demand for labour and capital in the intermediate good sector, bringing down aggregate investment. Given the imperfect complementarity between energy goods and non-energy consumption goods for households, the lower relative price of energy for consumption, lowers the demand for non-energy consumption goods, driving down overall consumption. The decline in investment in the intermediate good sector combined with the overall fall in consumption contribute to a decline in GDP.

Carbon subsidies A carbon subsidy (dotted red lines) is attached to the price of dirty energy, used for production of the dirty energy good, which is demanded, together with clean energy, for production of aggregate energy. Overall, as will become clear, the effects of a carbon subsidy on inflation and real activity lie inbetween those of a subsidy on energy consumption and a subsidy on energy production.

The subsidized dirty energy price leads aggregate energy producers to limit their substitution towards clean energy that arises as a result of the fossil price shock, and towards utilizing the now less costly, subsidized dirty energy. Similar to the effects f the fossil resource price shock, the degree to which this occurs is driven by the elasticity of substitution between clean and dirty energy, ϵ_e, which in line with empirical evidence in Papageorgiou et al. (2017) is calibrated equal to 1.8, motivating the case of imperfect substitutatibility between the two inputs. Inverseley to a fossil resource price shock however, the aggregate (post-tax) price of aggregate energy now falls, while energy used for production and consumption increases, as the subsitution towards dirty energy compensates for the relative reduction in clean energy.

The lower aggregate energy price faced by firms limits the increase in core inflation, by mitigating the increase in marginal costs of intermediate good firms, while the lower energy price faced by households for consumption of energy goods contributes to a decline in CPI inflation. However, since the passthrough of the dirty energy price into the aggregate enery price is mitigated by nominal rigidities at the level of dirty energy production, the effects on core inflation are more modest relative to the energy production subsidy. Equivalently, they are also more modest on CPI inflation relative to the energy consumption subsidy. As a result, the effects on aggregate consumption and investment, and hence GDP, lie inbetween the cases of subsidies on energy production and energy consumption.

4.2 Effects on the financial sector and carbon emissions

Figure 9 illustrates the effects on financial sector variables and on carbon emissions.

The presence of financial frictions contributes towards amplifying the mechanisms previously discussed. The subsidy on energy production as well as the carbon subsidy increase capital demand of non-financial firms, putting downward pressure on clean and dirty energy asset prices, and limit the increase in lending spreads, particularly those of the intermediate good sector, which represents a sizeable share of the economy. As a result, the balance sheet of financial intermediaries improves relative to the case without subsidies, leading their leverage constraint to become less binding, and asset prices to increase. Overall, the adverse feedback loop between non-financial firms and financial intermediaries is mitigated following energy production and carbon subsidies.

However, an energy consumption subsidy does little to affect bank net worth and lending spreads, deriving from the fact that overall consumption and intermediate good production declines relative to the case without subsidies. This occurs because the energy consumption subsidy increases the relative price of non-energy consumption goods, and puts upward pressure on intermediate good firms marginal costs by affecting the (after-subsidy) aggregate energy price, following from an increase in production of (clean and dirty) energy to meet the increased demand for its consumption. In this case, while overall bank net worth remains unchanged, the portfolio composition of banks is shifted towards dirty and clean energy producers rather than intermediate good producers.

Finally, recall that emissions are a byproduct of production in the dirty energy sector. Therefore, as production of dirty energy responds following changes in energy-related subsidies, emissions also respond proportionately. A carbon subsidy, which rewards the production of dirty energy by lowering its price, although balanced in terms of its impact on inflation and output, leads to the largest increase in carbon emissions relative to the case without subsidies. Instead, energy consumption and production subsidies only modestly increases emissions, as they do not significantly affect the relative prices of dirty and clean energy inputs, utilized for the production of aggregate energy.

4.3 Robustness

We explore the robustness of our results against alternatives that differ in the steady-state shares of energy used for consumption and production, the elasticity of substitution affecting different energy inputs in the corresponding CES aggregators, and alternative monetary policy rules, targeting CPI vs. core inflation.

4.3.1 Shares of energy in production and consumption

Figure A.1 in the Appendix illustrates impulse responses following a fossil resource prick shock (black lines) and impulse responses following an energy production subsidy (green lines), an energy consumption subsidy (blue lines), and a carbon subsidy (red lines). It compares the results from our original calibration against the case of a higher share of energy in production, (15% instead of 8%; dashed lines), and against a calibration with a higher share of energy in consumption, (15% instead of 5%; dotted lines). The fossil resource price shock remains as in Figure 2, while subsidies are separate AR(1) processes of magnitude 1% of GDP with persistence equal to 0.85.

The results indicate that overall higher energy shares amplify the effects of fossil price shocks as well of all subsidies, and operate through their effects on magnifying the change in the price of the aggregate consumption bundle (in the case of higher energy used in consumption) and through a larger change in intermediate good firms' marginal costs (in the case of higher energy used in production.

The real effects of subsidies and fossil price shocks follow the dynamics and mechanisms described above, with analogous amplification depending on the calibration of energy shares. Qualitatively however, the relative effects across subsidies are maintained under the alternative calibrations. It is worth highlighting, that regardless of the calibration of energy shares, an energy production subsidy uniquely operates by affecting the demand for energy for intermediate good producers and hence energy used for production, with negligible differential effects on the consumption of energy.

Regarding carbon emissions, the effects are correspondingly larger the higher the share of energy in consumption and production, with carbon subsidies yielding the largest increase across energy-related subsidies, due to the fact that they operate by lowering the relative price of dirty energy.

4.3.2 Elasticities of substitution across different inputs

Figures A.2 - A.4 in the Appendix provide a sensitivity around different calibration assumptions surrounding the elasticities of substitution of different CES bundles.

Figure A.2 performs a sensitivity analysis around ϵ_e, the elasticity of substitution of between dirty and clean energy inputs required to produce the aggregate energy bundle. For higher values of ϵ_e, the ability of aggregate energy providers to reallocate across clean vs.

dirty energy inputs becomes easier in the medium-term. Following fossil price shocks and carbon subsidies, the effects on inflation and on emissions are mitigated (less inflationary with a lower drop in emissions following fossil price shocks, and less disinflationary and lower increase in emissions following carbon subsidies). Moreover, for a lower ϵ_e, implying imperfect complementarity between clean vs. dirty energy inputs, the real and nominal effects follow the same dynamics, however rather than occurring through a weaker reallocation across energy sectors, the effects operate by reducing the aggregate production of energy by more. This contributes to a dampened increase in emissions following carbon subsidies. Notably, as ϵ_e only affects the reallocation across energy sectors, energy consumption and energy production subsidies yield the same effects as they operate on the aggregate energy price faced by firms and households.

Next, Figure A.3 performs a sensitivity analysis around ϵ_m, the elasticity of substitution of between value added and energy required to produce the intermediate good used for final consumption and investment purposes. For higher values of ϵ_m, the ability of intermediate good firms to substitute away from more costly energy following fossil price shocks leads to a reduction in the production of energy, but an increase in the use of capital and labour for production of the intermediate good. Overall, this puts upward pressure on core and CPI inflation, while emissions fall by more. The analogous inverse mechanism is operative for subsidies on the production of energy, implying greater disinflationary effects combined with a stronger increase in the use of energy for production and emissions. The effects of energy consumption subsidies instead are similar across different values of ϵ_m, as they operate on affecting the relative price of energy faced by households, and contribute little to raising firm marginal costs (and hence core inflation) following only a negligible increased demand for energy; this can be seen by the identical effects of different values of ϵ_m on energy consumption across subsidy types.

Finally, Figure A.4 performs a sensitivity analysis around ϵ_c, the elasticity of substitution between energy and non-energy goods in households' aggregate consumption bundles. For high values of ϵ_c, energy and non-energy consumption goods become more substitutable, suggesting that following fossil price shocks, which increase the price of aggregate energy, households more easily move towards non-energy goods for consumption purposes, lowering their energy consumption and mitigating the increase in CPI inflation. Instead, an energy consumption subsidy is now less disinflationary for high values of ϵ_c, and increases core inflation by more, as it lowers the relative price of energy goods in consumption by a greater magnitude. As a result, while energy used for production declines, the mix between dirty and clean energy inputs tilts towards the dirty energy sector, contributing towards a stronger increase in emissions. Notably, the effects of energy productions subsidies instead are similar across different values of ϵ_e, as they operate on affecting the relative price of energy faced by firms.

4.4 Fiscal and emission multipliers

The relative differences in magnitudes across different energy-related subsidies can be summarized informatively by reporting fiscal multipliers. We calculate fiscal multipliers in present value terms following Uhlig (2010). Formally, the present value multiplier at horizon h is given by:

$$M_t^{PV} = \frac{\sum_{h=0}^{t} \overline{R}^{-h} \left(\hat{X}_h - \overline{X} \right)}{\sum_{h=0}^{t} \overline{R}^{-h} \left(\hat{Rev}_h - \overline{Rev} \right)} \tag{67}$$

where $\overline{R}$ denotes the real interest rate on government debt at the steady state, and $\hat{X}_h$ and $\hat{Rev}_h$ are the responses of the variable of interest (e.g. output, emissions, etc.) and revenues, relative to their steady states, $\overline{X}$ and $\overline{Rev}$, respectively.

Figure 10 and Table 2 report present value fiscal multipliers for output and emissions following a 1% reduction in revenues (as a % of GDP) across different fiscal instruments. In line with the discussion in section 4.1 the present value multiplier for the energy production subsidy is largest from period 4 onwards and converges to 1.67 in the long run. Instead, the energy consumption subsidy implies a negative present value multiplier throughout the horizon and converges to -0.26 in the long run. The carbon subsidy produces an intermediate effect, with a present value multiplier greater than 1 in the long run.

Regarding carbon emissions, their path is proportionate to the increase in the production of dirty energy. Therefore, a carbon subsidy which lowers the relative price of dirty energy leads to the highest emission multiplier, which is around 6 in the long run. Following again the discussion in section 4.1, the long run emission multiplier of the energy production subsidy is greater than the long run emission multiplier of the energy consumption subsidy.

We also compare against a reduction in VAT. In contrast to subsidies targeted at the price of energy (faced by different agents in the model), a VAT reduction lowers the price of aggregate consumption and is therefore blind to its composition between energy and non-energy consumption goods. As a result, the reduction in the relative price of consumption relative to the investment good, translates to an increase in overall consumption but at the expense of a decline in aggregate investment. Overall, while the effects on output are positive, they are quantitatively small leading to a present value multiplier on output that is 0.36 on impact but turns negative in the long run. Finally, given that a VAT decrease eventually lowers production, the present value emission multiplier for VAT converges to zero.

It becomes clear from the analysis, that relative to the available fiscal instruments, energy production subsidies are better suited to mitigate the contractionary effects of fossil price shocks in the medium term, while only modestly slowing down the transition to a low-carbon economy.

5 Macroprudential Policy

Energy subsidies evidently contribute towards temporarily slowing down the "green transition" brought about by an increase in fossil prices. The analysis in this section shows that a comprehensive set of macroprudential policies can be introduced to compensate for transition risks: When the government has access to macroprudential taxes and subsidies, which can be imposed on sectoral bank assets in bank portfolios, the emission increases from energy subsidies can be mitigated, without leading to adverse effects on macroeconomic outcomes.[7]

Given that banks face a moral hazard problem, macroprudential taxes and subsidies operate by affecting on the bank's ability to obtain deposits. Recall the expression for the value of the bank (eq. 68 from section 2) $V_t(N_t)$, which we now modify by introducing $\tau_{\Psi,f}$ and $\tau_{\Psi,g}$:

$$V_t(N_t) \geq \theta \left(Q_{m,t} S^b_{m,t} + (1+\tau_{\Psi,f}) \Psi_f Q_{f,t} S^b_{f,t} + (1+\tau_{\Psi,g}) \Psi_g Q_{g,t} S^b_{g,t} \right) \tag{68}$$

where Ψ_g, Ψ_f are sectoral absconding rates and $\tau_{\Psi,g}$, $\tau_{\Psi,g}$ are macroprudential taxes (subsidies when negative).

The macroprudential policies effectively introduce imperfect substitutablity between different securities in the bank's balance sheet and therefore to limited arbitrage. They are inherently equivalent to motivating sector-specific absconding rates in terms of imposing differential risk on assets in steady state portfolios, with the difference that macroprudential policies involve fiscal redistribution through the government to agents. Notably, such a macroprudential tax-subsidy policy scheme is also employed by Aoki et al. (2016) and Carattini et al. (2021), among others.

The different taxes/subsidies attached to intermediate good, clean and dirty energy sector assets motivating their imperfect substituability in bank portfolios can be rationalized following empirical evidence. For example Bolton and Kacperczyk (2021); Pastor et al. (2021); Pedersen et al. (2021)) show that the risk premium of green assets is negative . Through these sector-specific macorprudential policies, the policymaker can therefore emphasize the systematic market risk associated with e.g., brown assets, such as carbon pricing, regulation, reputational concerns, asset stranding and climate hedging risks. Instead, a macroprudential subsidy on clean energy assets can reflect the recent high demand for green assets from Environmental, Social, and Governance (ESG) investors lowering their expected return.

Figure 11 illustrates the case of a "Brown macroprudential policy", where the policymaker places a tax on dirty energy assets (dashed red lines) compared to the case of a "Green macroprudential" policy where instead a subsidy is placed on clean energy assets (dotted green lines). Solid blue lines refer to the benchmark without any macroprudential

[7] An additional policy tool which the central bank can employ to alter the portfolio compositions of financial intermediaries consists of sectoral asset purchases. However, given the more sizeable macroeconomic effects of such a policy it would also undo some of the effects of energy subsidies towards mitigating the inflationary consequences of fossil resource price shocks.

policies.

A macroprudential tax on dirty energy assets in bank balance sheets tilts bank portfolios away from dirty energy assets and into assets used for the production of clean energy and for the intermediate good. So, while the policy enables the dirty energy asset price to decline by less, less bank financing is extended to dirty energy firms for production of the dirty energy input, which is instead allocated to clean energy firms and firms that produce the intermediate good. Given the large share of intermediate good assets in production, aggregate investment and output fall by less. At the same time, since the banking sector becomes less exposed to dirty energy, bank equity drops by less, "green investment" increases by more, and the reduction in emissions is stronger.

Instead, a macroprudential policy that subsidizes clean energy assets (dotted green lines) tilts bank portfolios towards clean energy assets and away from dirty energy assets. The increase in clean energy investment is more sizeable under such a policy, as the macroprudential subsidy lowers the clean energy asset price more significantly, preventing banks from investing in dirty energy assets with higher excess returns. Similar to the"Brown" macroprudential policy, a "Green" macroprudential policy also mitigates the contraction in GDP but contributes less towards reducing emissions.

We then ask to what extent the alternative macroprudential tools presented above can complement the different energy subsidies in mitigating the ensuing increase in carbon emissions from fiscal policy, while not distorting the macroeconomic benefits provided by them. Tables 3 to 6 report the stabilization properties of different configurations of energy subsidies with "Green" and "Brown" macroprudential polices against a fossil price shock, by reporting the variance of CPI and core inflation, GDP and consumption, lending spreads, and carbon emissions, calculated as the percent (or percentage point) deviation of each variable from its steady state value over 40 quarters.

The results illustrate that absent macroprudential policy, energy subsidies (either on the production, or consumption side, but also carbon taxes) stabilize inflation rates, real activity, lending spreads, while increasing carbon emissions, in line with the discussion in section 4. Allowing for "Brown" and "Green" macroprudential policies contributes to less stabilization of carbon emissions, which now implies their greater decline, while real and nominal variables are little affected. Since the policies operate by affecting the corresponding asset prices, "Brown" macroprudential policy primarily operates by stabilizing dirty energy lending spreads, while "Green" macroprudential policy by stabilizing clean energy lending spreads, in relative terms.

6 Conclusion

This paper has developed a New-Keynesian E-DSGE model featuring energy disaggregation and financial intermediaries to comprehensively understand the propagation and interaction of production-side and consumption-side energy-related subsidies as well as macroprudential policies through the bank lending channel. Our analysis shows that relative to the fossil price shock, an energy production subsidy can lower both core inflation (i.e. inflation excluding energy) and CPI inflation and increase aggregate output, while an energy consumption subsidy can only lower CPI inflation, but increase core inflation and reduce aggregate output. In turn, a carbon subsidy, lies in the middle, lowering both CPI and core inflation and increasing aggregate output, but to less of an extent relative to the energy production subsidy. Given that such instruments are targeted at raising the production of energy, to the extent that additional dirty energy is used for production, carbon emissions increase.

Recognizing that energy subsidies contribute towards temporarily slowing down the "green transition" that is brought about by an increase in fossil prices, we have evaluated how a comprehensive set of macroprudential policies can be introduced to compensate for the newly emerging transition risks. When the government has access to macroprudential taxes and subsidies, which can be imposed on sectoral bank assets in bank portfolios, the emission increases from energy subsidies can be mitigated, without leading to adverse effects on macroeconomic outcomes.

Notably, our closed economy model does not capture the changes in domestic vis a vis international relative prices that may materialize as a result of changes in the supply of fossil resources, which from the perspective of the EA are typically imported. Allowing for fossil resources to be imported via the modeling of a second fossil-exporting region is an extension of the model that can be pursued in future research, which would arguably not meaningfully impact the the qualitative predictions of the analysis, but have implications for the magnitudes of the responses of real and nominal variables following energy-related subsidies.

An additional consideration absent in our model relates to the modeling of endogenous technological change, which arguably will impact the effects of energy-related subsidies over the medium to longer term, as the efficiency of clean energy improves thereby placing downward pressure on the price of clean energy assets. We leave this to future research.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012): "The Environment and Directed Technical Change," *American Economic Review*, 102, 131–166.

Airaudo, F., E. Pappa, and S. H. (2022): "Greenflation: The cost of the green transition in small open economies," mimeo.

Annicchiarico, B. and F. Di Dio (2015): "Environmental policy and macroeconomic dynamics in a new Keynesian model," *Journal of Environmental Economics and Management*, 69, 1–21.

Aoki, K., G. Benigno, and N. Kiyotaki (2016): "Monetary and Financial Policies in Emerging Markets," Working Papers 2016-4, Princeton University. Economics Department.

Auclert, A., H. Monnery, M. Rognlie, and L. Straub (2023): "Managing an Energy Shock: Fiscal and Monetary Policy," Tech. rep., Working Paper.

Bachmann, R., D. Baqaee, C. Bayer, M. Kuhn, A. Löschel, B. Moll, A. Peichl, K. Pittel, and M. Schularick (2022): "What if Germany is cut off from Russian energy?" *VoxEU. org*, 25.

Baqaee, D. and E. Farhi (2022): "Supply and demand in disaggregated Keynesian economies with an application to the Covid-19 crisis," *American Economic Review*, 112, 1397–1436.

Baqaee, D. R. and E. Farhi (2019): "The macroeconomic impact of microeconomic shocks: Beyond Hulten's theorem," *Econometrica*, 87, 1155–1203.

Bartocci, A., A. Notarpietro, and M. Pisani (2022): ""Green" fiscal policy measures and non-standard monetary policy in the euro area," Temi di discussione (Economic working papers) 1377, Bank of Italy, Economic Research and International Relations Area.

Benmir, G. and J. Roman (2020): "Policy Interactions and the Transition to Clean Technology," Working Paper 368, Centre for Climate Change Economics and Policy.

Bodenstein, M., C. J. Erceg, and L. Guerrieri (2011): "Oil shocks and external adjustment," *Journal of International Economics*, 83, 168–184.

Bolton, P. and M. Kacperczyk (2021): "Do investors care about carbon risk?" *Journal of Financial Economics*, 142, 517–549.

Calvo, G. A. (1983): "Staggered Prices in a Utility-Maximizing Framework," *Journal of Monetary Economics*, 12, 383 – 398.

Carattini, S., G. Heutel, and G. Melkadze (2021): "Climate Policy, Financial Frictions, and Transition Risk," NBER Working Papers 28525, National Bureau of Economic Research, Inc.

Christiano, L. J., M. Eichenbaum, and C. L. Evans (2005): "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy*, 113, 1–45.

Coenen, G., P. Karadi, S. Schmidt, and A. Warne (2018): "The New Area-Wide Model II: an extended version of the ECB's micro-founded model for forecasting and policy analysis with a financial sector," Working Paper Series 2200, European Central Bank.

Coenen, G., M. Lozej, and R. Priftis (2023): "Macroeconomic Effects of Carbon Transition Policies: An Assessment Based on the ECB's New Area-Wide Model With a Disaggregated Energy Sector," mimeo, European Central Bank.

Diluiso, F., B. Annicchiarico, M. Kalkuhl, and J. C. Minx (2021): "Climate actions and macro-financial stability: The role of central banks," *Journal of Environmental Economics and Management*, 110.

Erceg, C. J., M. Kolasa, J. Lindé, and M. A. Pescatori (2024): "Can Energy Subsidies Help Slay Inflation?" IMF Working Papers 2024/081, International Monetary Fund.

Ferrari, A. and V. Nispi-Landi (2022): "Will the green transition be inflationary? Expectations matter," Working Paper Series 2726, European Central Bank.

Gertler, M. and P. Karadi (2011): "A Model of Unconventional Monetary Policy," *Journal of Monetary Economics*, 58, 17–34.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014): "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica*, 82, 41–88.

Känzig, D. R. (2023): "The Unequal Economic Consequences of Carbon Pricing," NBER Working Papers 31221, National Bureau of Economic Research, Inc.

Karadi, P. and A. Nakov (2020): "Effectiveness and Addictiveness of Quantitative Easing," *Journal of Monetary Economics*, forthcoming.

Kharroubi, E. and F. Smets (2023): "Energy shocks as Keynesian supply shocks: implications for fiscal policy," BIS Working Papers 1120, Bank for International Settlements.

Nakov, C. and C. Thomas (2023): "Climate-Conscious Monetary Policy," mimeo.

Papageorgiou, C., M. Saam, and P. Schulte (2017): "Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective," *The Review of Economics and Statistics*, 99, 281–290.

Pastor, L., R. F. Stambaugh, and L. A. Taylor (2021): "Sustainable investing in equilibrium," *Journal of Financial Economics*, 142, 550–571.

Pataracchia, B., P. Pfeiffer, M. Ratto, and J. Teresinski (2023): "Energy prices as drivers of inflation and real output: An estimated structural model for the euro area," Tech. rep., unpublished manuscript.

Pedersen, L. H., S. Fitzgibbons, and L. Pomorski (2021): "Responsible investing: The ESG-efficient frontier," *Journal of Financial Economics*, 142, 572–597.

Sgaravatti, G., S. Tagliapietra, T. C., and G. Zachmann (2023): "National policies to shield consumers from rising energy prices," Bruegel Datasets first published in 2021, Bruegel.

Smets, F. and R. Wouters (2007): "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," *American Economic Review*, 97, 586–606.

Uhlig, H. (2010): "Some Fiscal Calculus," *American Economic Review*, 100, 30–34.

Varga, J., W. Roeger, and J. in't Veld (2021): "E-QUEST - A Multi-Region Sectoral Dynamic General Equilibrium Model with Energy Model Description and Applications to Reach the EU Climate Targets," European Economy - Discussion Papers 2015 - 146, Directorate General Economic and Financial Affairs (DG ECFIN), European Commission.

Figure 1: A schematic illustration of the model's structure

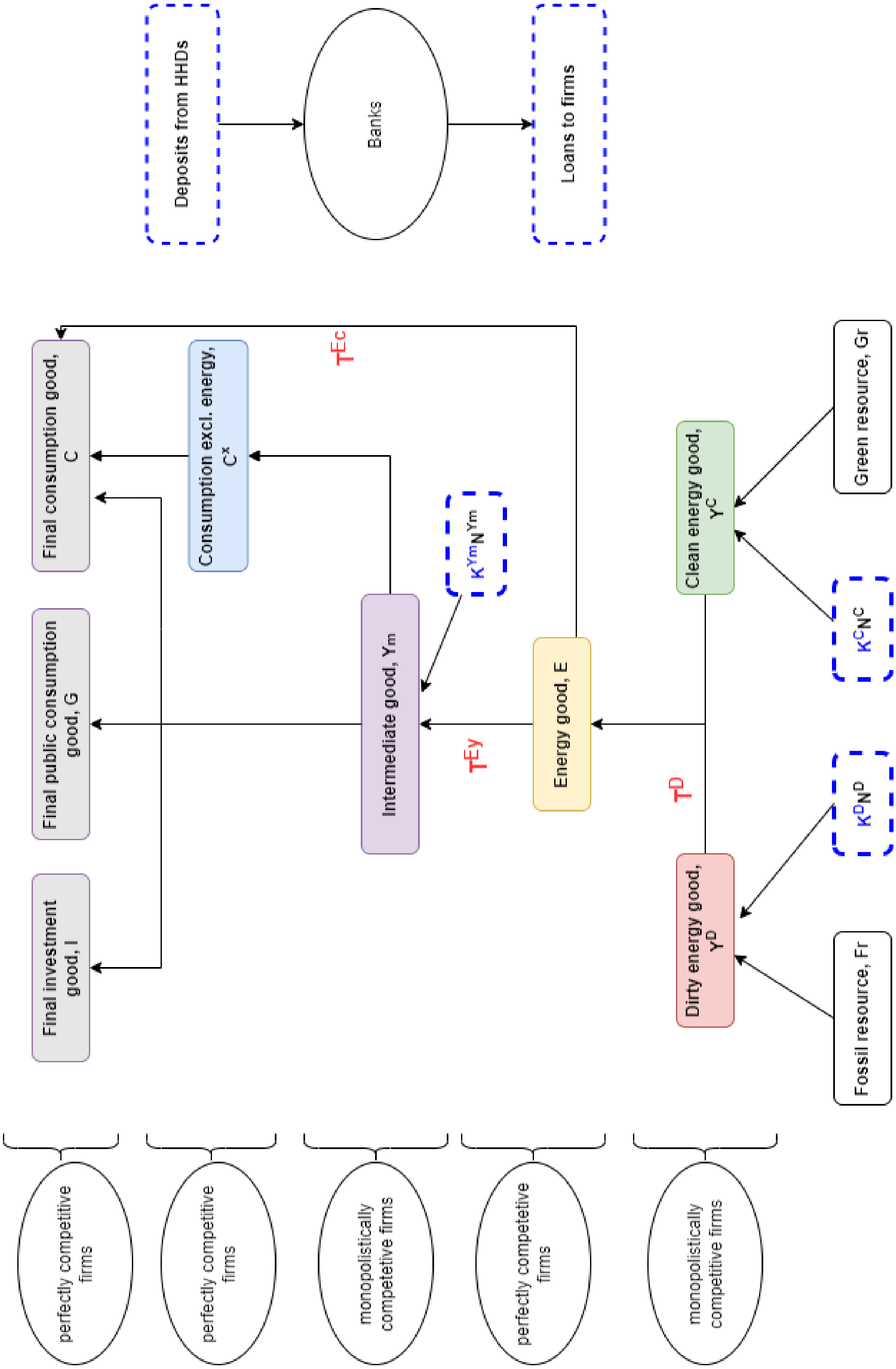
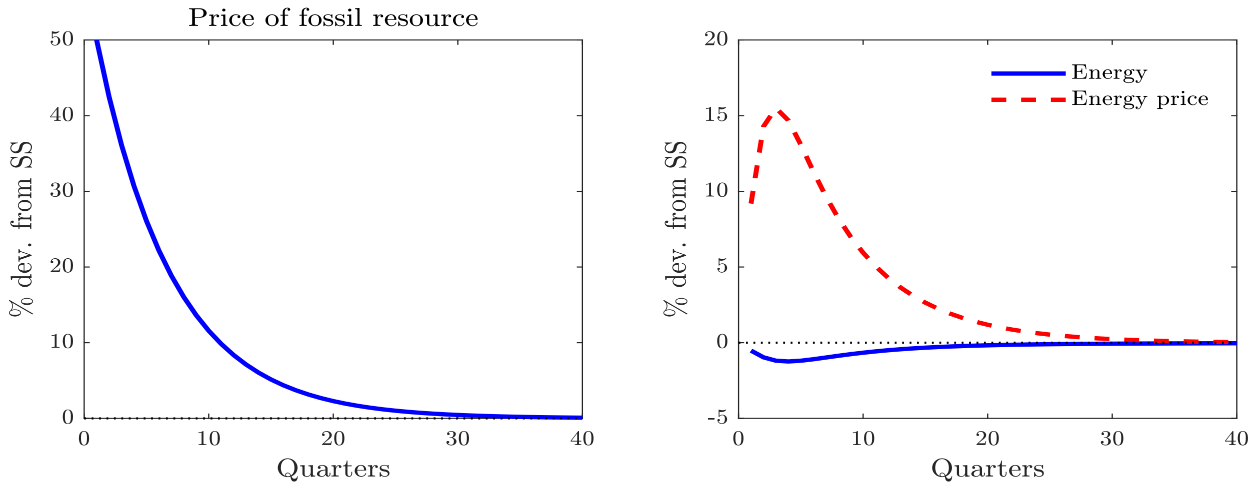


Table 1: Parameter values

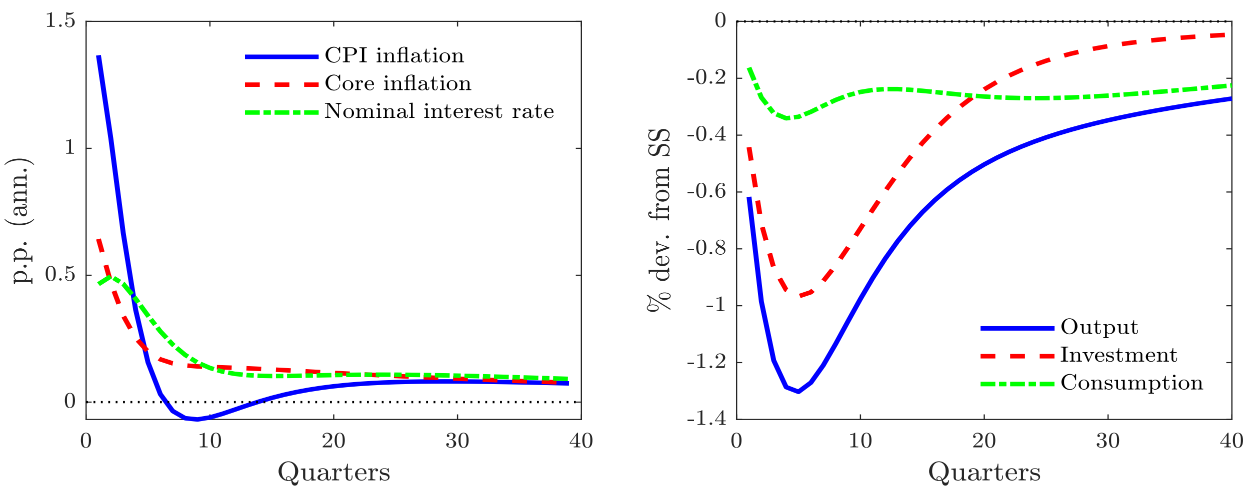
	Households	
β	0.995	Discount factor
γ	1.5	Risk aversion coefficient
h	0.62	Habit
φ	0.7	Inverse of the Frisch elasticity of labor supply
χ	25	Disutility of labor
ω_c	0.05	Quasi-share of energy in consumption
ϵ_c	0.4	El. of subst. energy and non-energy good
	Goods producers	
ϵ	6	El. of subst. between final goods varieties
ω_m	0.92	Quasi-share of value added
ϵ_m	0.4	El. of subst. value added and energy
α_m	0.33	Capital share, value added
δ_m	0.025	Depreciation rate
ψ_m	0.92	Probability of keeping the price fixed
	Energy producers	
ω_e	0.3	Quasi-share of clean energy
ϵ_e	1.8	El. of subst. clean and dirty energy
ω_g, ω_f	0.3, 0.3	Quasi-share of value added
ϵ_g, ϵ_f	0.25, 0.25	El. of subst. energy input and natural resource
α_g, α_f	0.33, 0.33	Capital share, value added
δ_g, δ_f	0.0125, 0.02	Depreciation rate
ψ_g, ψ_g	0.25, 0.25	Probability of keeping the price fixed
ϖ	380	Carbon intensity
	Financial intermediaries	
σ	0.955	Survival rate of bankers
θ	0.18	Fraction of divertible funds
ψ_g	0.8	Relative absconding rate, clean assets
ψ_f	1.2	Relative absconding rate, dirty assets
κ	0.0129	Transfers to new bankers
	Government	
$\bar{g}$	0.21	Share of government consumption, steady state
κ_i	0.8	Taylor rule, smoothing
κ_π	2	Taylor rule, weight on inflation
κ_y	0.1	Taylor rule, weight on output

Figure 2: Shock to the fossil resource price



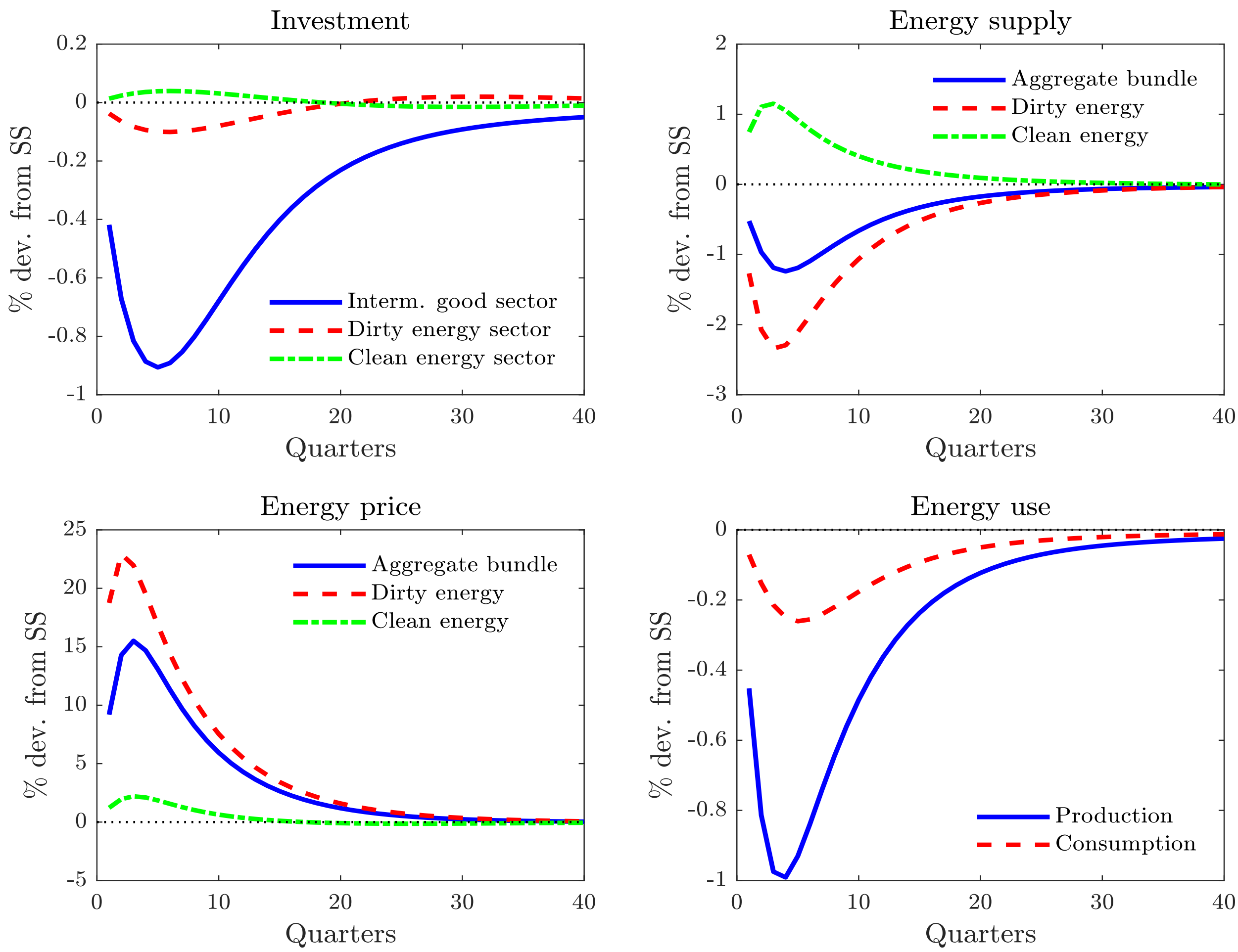
Notes: A temporary increase in the fossil resource price by 50% following an AR(1) process with persistence 0.85.

Figure 3: Aggregate effects of a fossil resource price shock



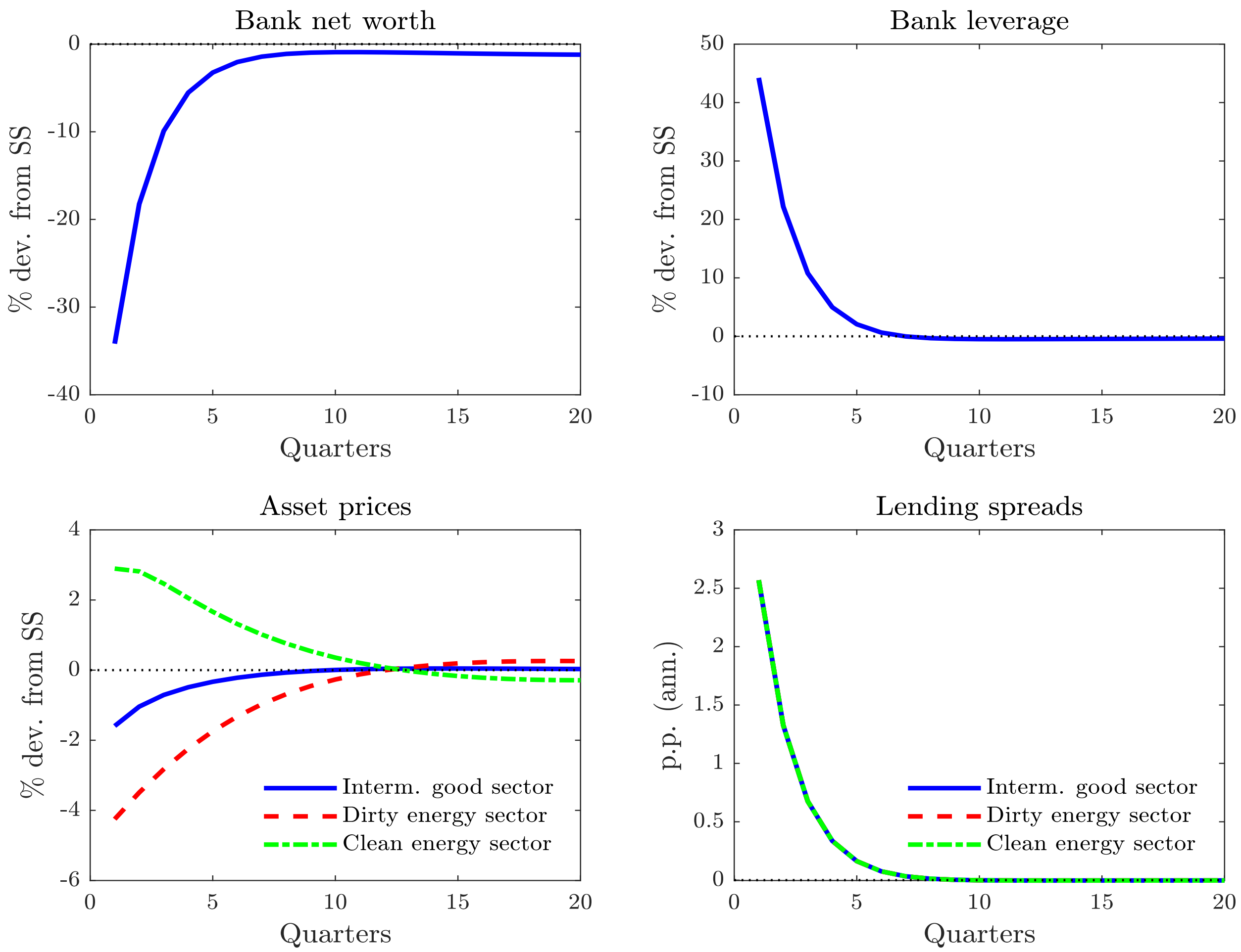
Notes: Impulse responses to the fossil resource price shock shown in Figure 2

Figure 4: Sectoral effects of a fossil resource price shock



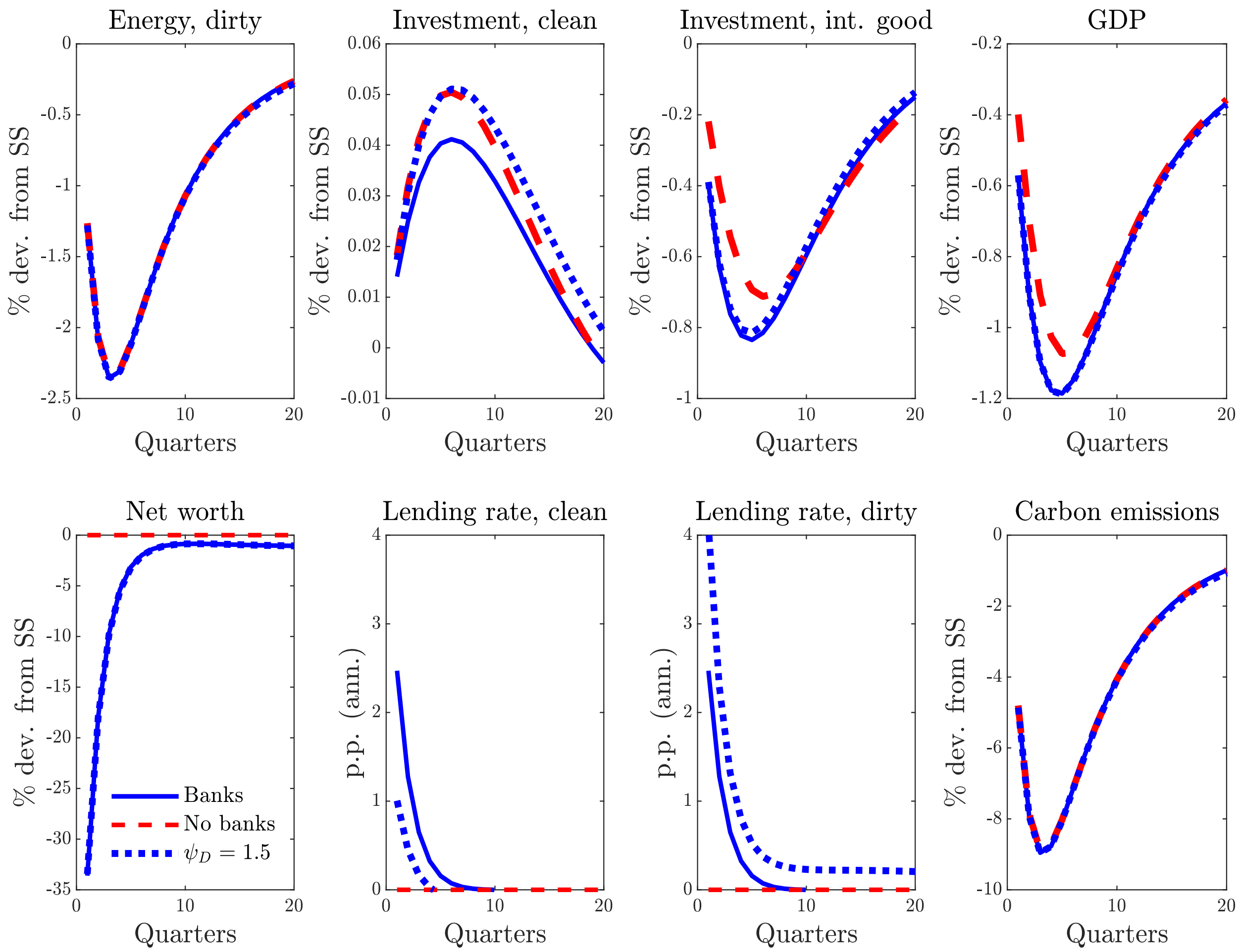
Notes: Impulse responses to the fossil resource price shock shown in Figure 2

Figure 5: Financial sector effects of a fossil resource price shock



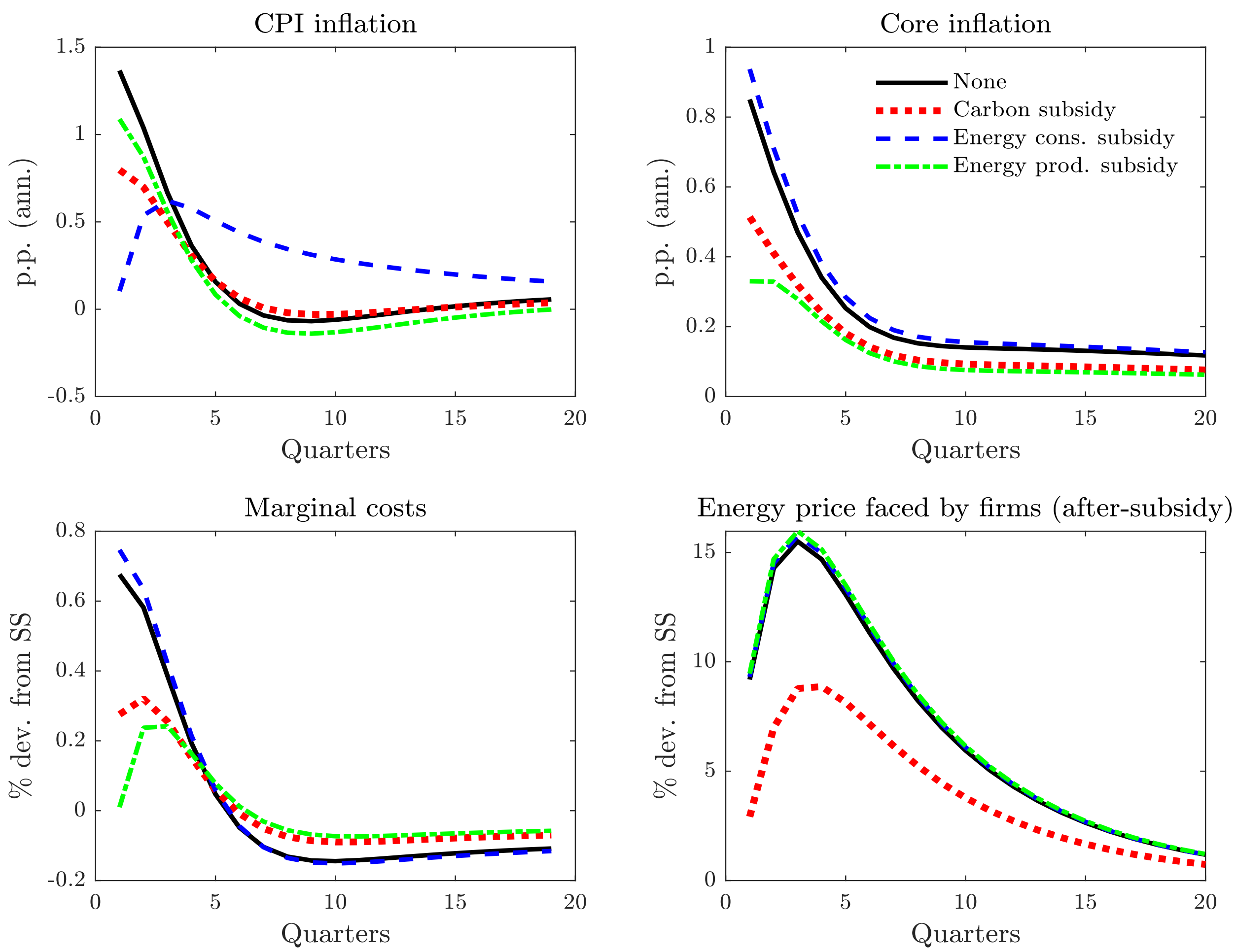
Notes: Impulse responses to the fossil resource price shock shown in Figure 2

Figure 6: Role of financial frictions



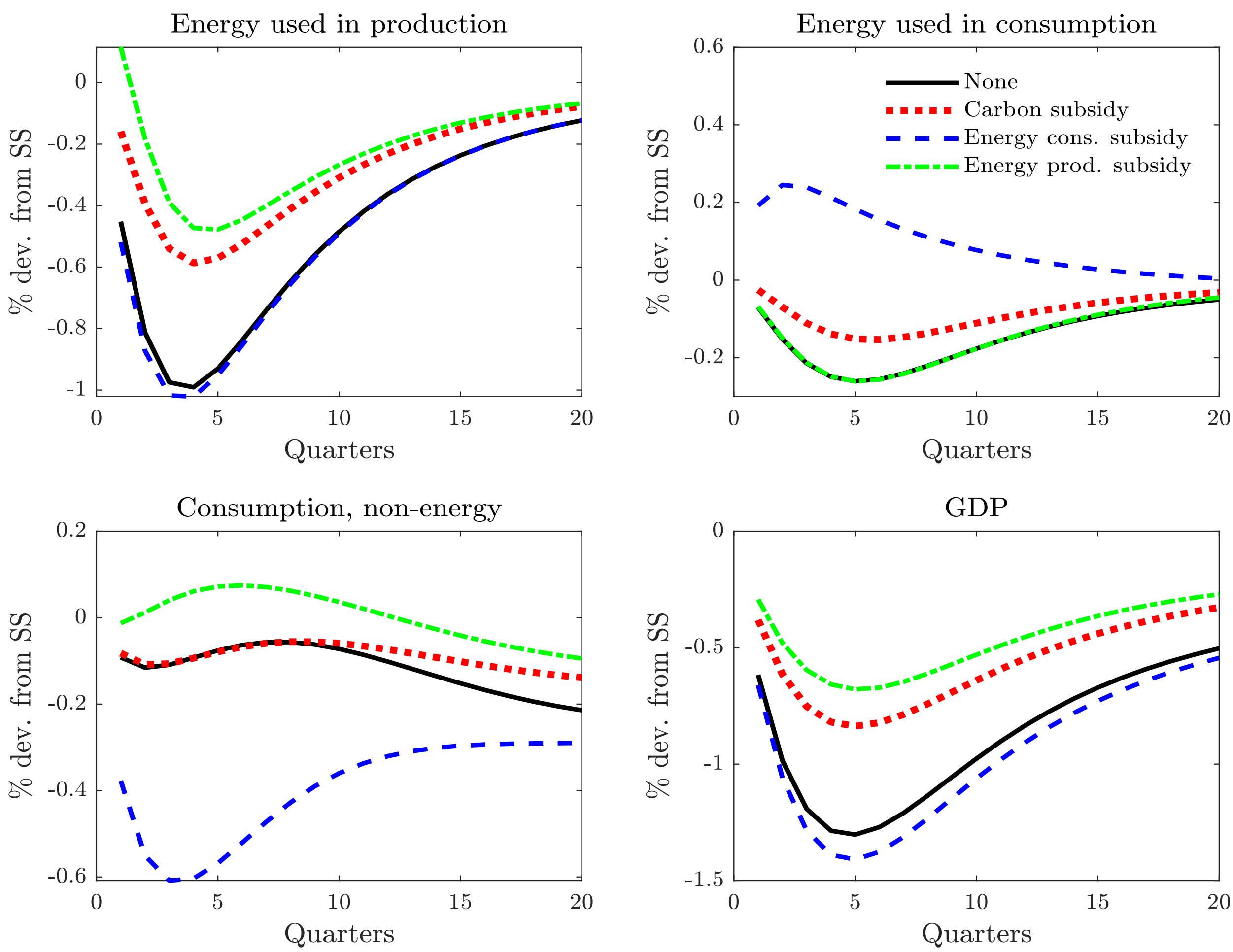
Notes: Impulse responses to the fossil resource price shock shown in Figure 2 in a model with leverage-constrained banks (blue lines) and without banks (dashed red lines). Solid blue lines refer to the economy with equal absconding rates across assets ($\psi_f = \psi_g = 1$). Dashed blue lines refer to the case where $\Psi_f = 1.5, \Psi_g = 1$

Figure 7: Effects of energy subsidies on prices



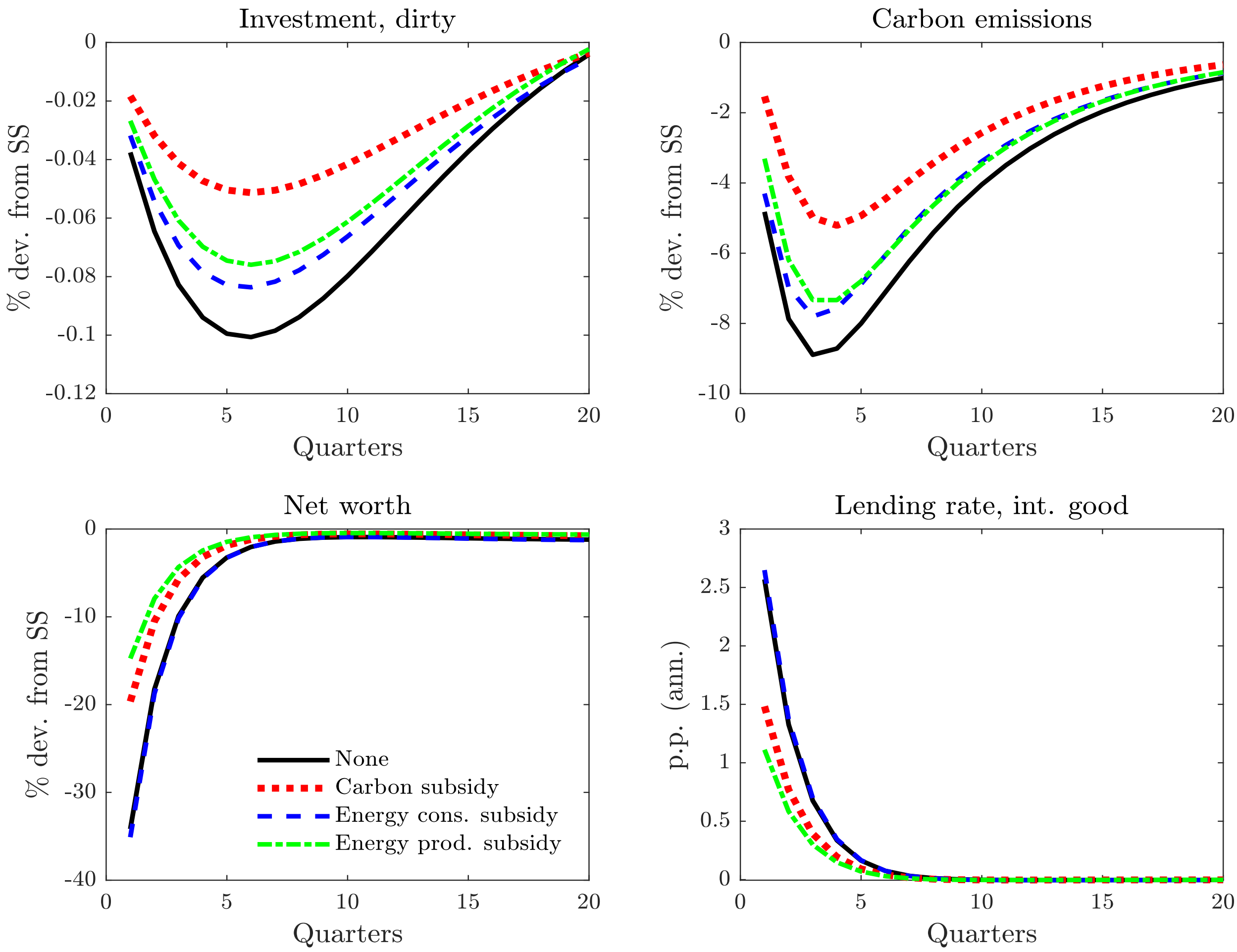
Notes: Impulse responses from alternative energy-related subsidies following a resource price shock as in Figure 2. Black solid lines refer to the case of no subsidies.

Figure 8: Effects of energy subsidies on the real economy



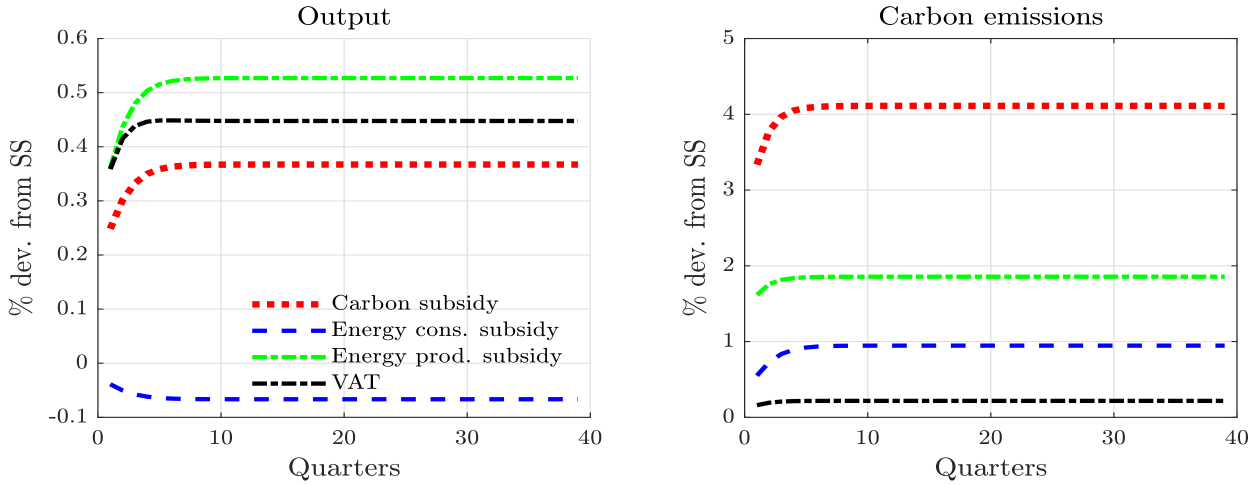
Notes: Impulse responses from alternative energy-related subsidies following a resource price shock as in Figure 2. Black solid lines refer to the case of no subsidies.

Figure 9: Effects of energy subsidies on the financial sector and carbon emissions



Notes: Impulse responses from alternative energy-related subsidies following a resource price shock as in Figure 2. Black solid lines refer to the case of no subsidies.

Figure 10: Present value fiscal multipliers for output and emissions



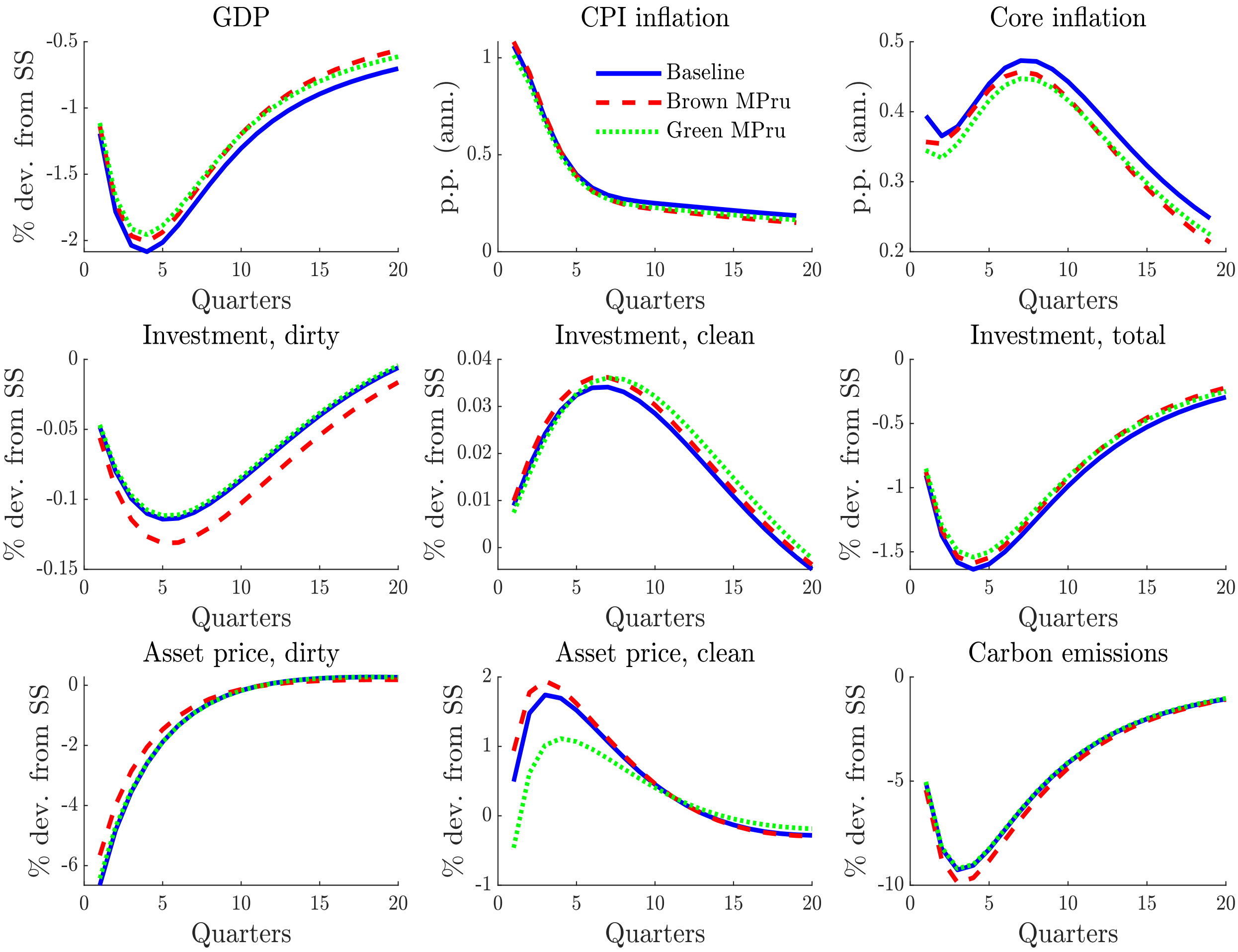
Notes: Present value fiscal multipliers for GDP and carbon emissions following a temporary increase in energy subsidies equivalent to an (ex-ante) 1% of GDP loss in government revenue, following an AR(1) process with persistence 0.85. Present value multipliers are calculated as in eq. 67.

Table 2: Present value fiscal multipliers for different fiscal instruments

	Quarters				
	$t=1$	$t=4$	$t=8$	$t=12$	Long run
GDP					
τ^{E^y}	0.36	0.48	0.52	0.53	0.53
τ^{E^c}	-0.04	-0.06	-0.07	-0.07	-0.07
τ^{P_d}	0.25	0.33	0.37	0.37	0.37
τ^{c}	0.36	0.44	0.45	0.45	0.45
Carbon emissions					
τ^{E^y}	1.62	2.03	2.15	2.21	2.47
τ^{E^c}	0.55	1.25	1.71	1.90	2.05
τ^{P_d}	3.34	4.67	5.12	5.30	5.74
τ^{c}	0.16	0.26	0.27	0.25	0.05

Notes: Present value fiscal multipliers for GDP and carbon emissions following a temporary increase in energy subsidies equivalent to an (ex-ante) 1% of GDP loss in government revenue, following an AR(1) process with persistence 0.85. Present value multipliers are calculated as in eq. 67

Figure 11: Effects of macroprudential policies



Notes: Impulse responses to the fossil resource price shock shown in Figure 2 "Brown" macroprudential policy ($\tau_{\psi,D} = -0.001$; dashed red lines) and "Green" macroprudential policy ($\tau_{\psi,C} = -0.001$; dotted green lines). Solid blue lines correspond to the case without macroprudential policies ($\tau_{\psi,D} = \tau_{\psi,C} = 0$)

Table 3: Stabilization effects of fiscal-macroprudential policy packages - inflation

	CPI inflation			Core inflation		
	Baseline	Brown Mpru	Green Mpru	Baseline	Brown Mpru	Green Mpru
No subsidy	0.059	0.067	0.059	0.015	0.017	0.015
τ^{E^y}	0.061	0.033	0.026	0.004	0.015	0.013
τ^{E^c}	0.022	0.011	0.009	0.015	0.019	0.018
τ^{P_d}	0.042	0.022	0.019	0.010	0.007	0.006

Notes: Variance of different macroeconomic variables following a fossil price shock, and when accompanied with different fiscal and macroprudential configurations. The variance is calculated over their percentage point deviation from their steady state values in annualized terms over 40 quarters.

Table 4: Stabilization effects of fiscal-macroprudential policy packages - output, consumption

	GDP			Consumption		
	Baseline	Brown Mpru	Green Mpru	Baseline	Brown Mpru	Green Mpru
No subsidy	0.257	0.294	0.257	0.001	0.002	0.001
τ^{E^y}	0.031	0.150	0.124	0.000	0.001	0.001
τ^{E^c}	0.133	0.087	0.066	0.002	0.004	0.004
τ^{P_d}	0.047	0.117	0.100	0.001	0.001	0.001

Notes: Variance of different macroeconomic variables following a fossil price shock, and when accompanied with different fiscal and macroprudential configurations. The variance is calculated over the % deviations of each variable from its steady state value over 40 quarters.

Table 5: Stabilization effects of fiscal-macroprudential policy packages - lending spreads

	Dirty energy			Clean energy		
	Baseline	Brown Mpru	Green Mpru	Baseline	Brown Mpru	Green Mpru
No subsidy	1.129	1.176	1.129	1.152	1.152	1.152
τ^{E^y}	0.040	0.732	0.687	0.040	0.717	0.701
τ^{E^c}	0.227	0.035	0.079	0.227	0.035	0.080
τ^{P_d}	0.071	0.377	0.347	0.071	0.370	0.354

Notes: Variance of different macroeconomic variables following a fossil price shock, and when accompanied with different fiscal and macroprudential configurations. The variance is calculated over their percentage point deviation from their steady state values in annualized terms over 40 quarters.

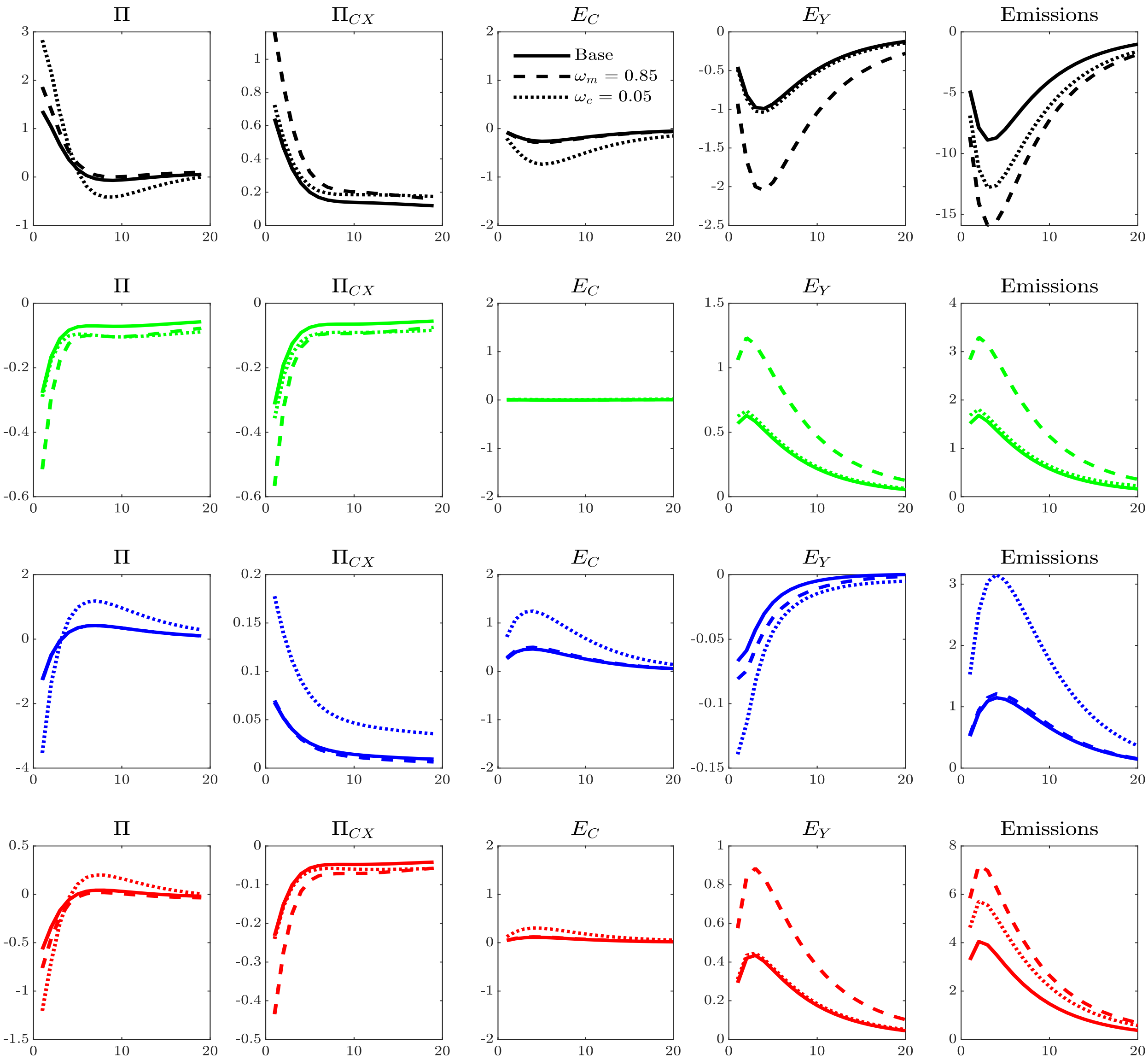
Table 6: Stabilization effects of fiscal-macroprudential policy packages - carbon emissions

	Carbon emissions		
	Baseline	Brown Mpru	Green Mpru
No subsidy	0.080	0.092	0.080
τ^{E^y}	0.052	0.065	0.56
τ^{E^c}	0.056	0.062	0.054
τ^{P_d}	0.026	0.032	0.027

Notes: Variance of different macroeconomic variables following a fossil price shock, and when accompanied with different fiscal and macroprudential configurations. The variance is calculated over the % deviations of each variable from its steady state value over 40 quarters.

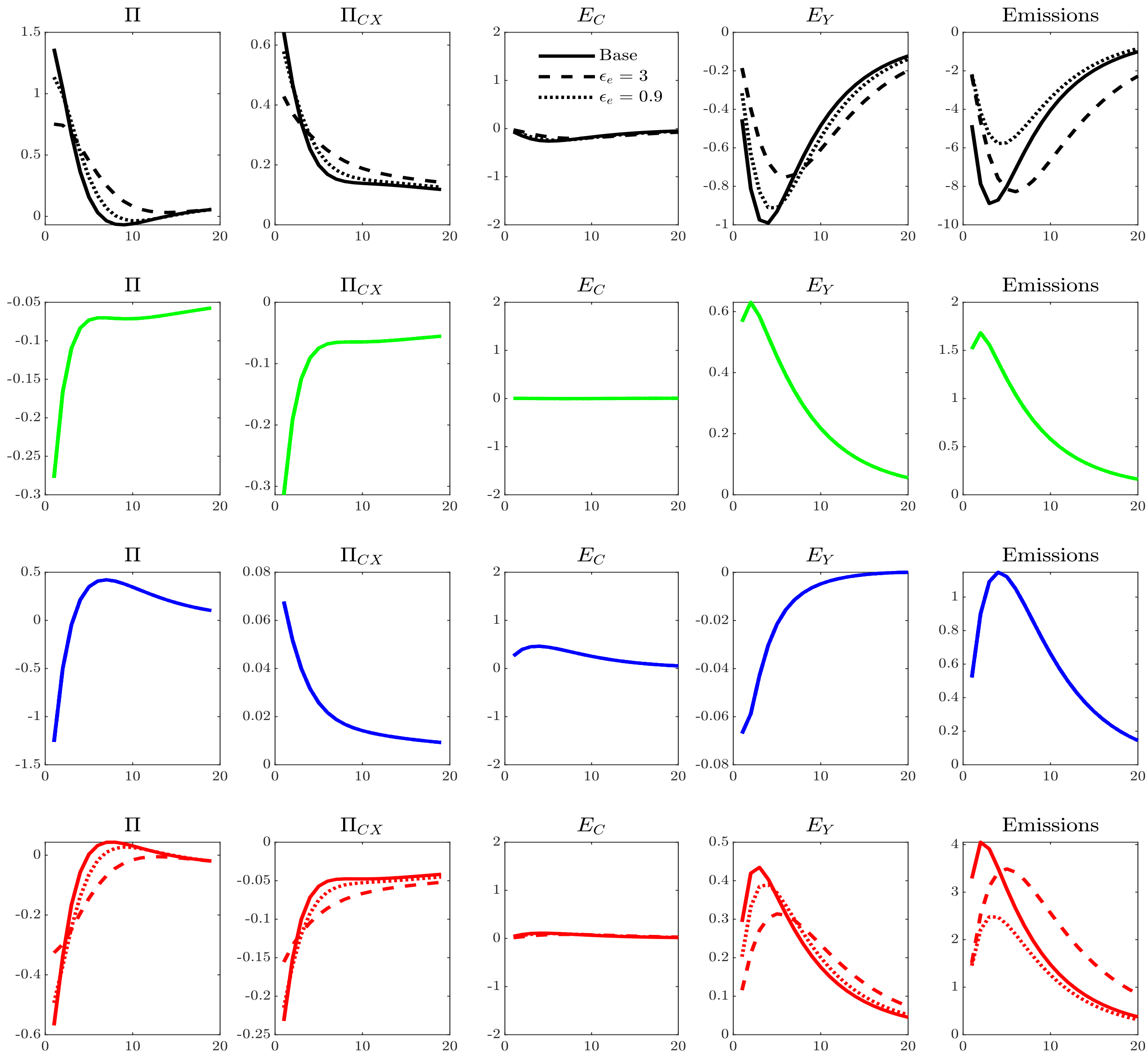
Appendix

Figure A.1: Robustness: Shares of energy in consumption and production



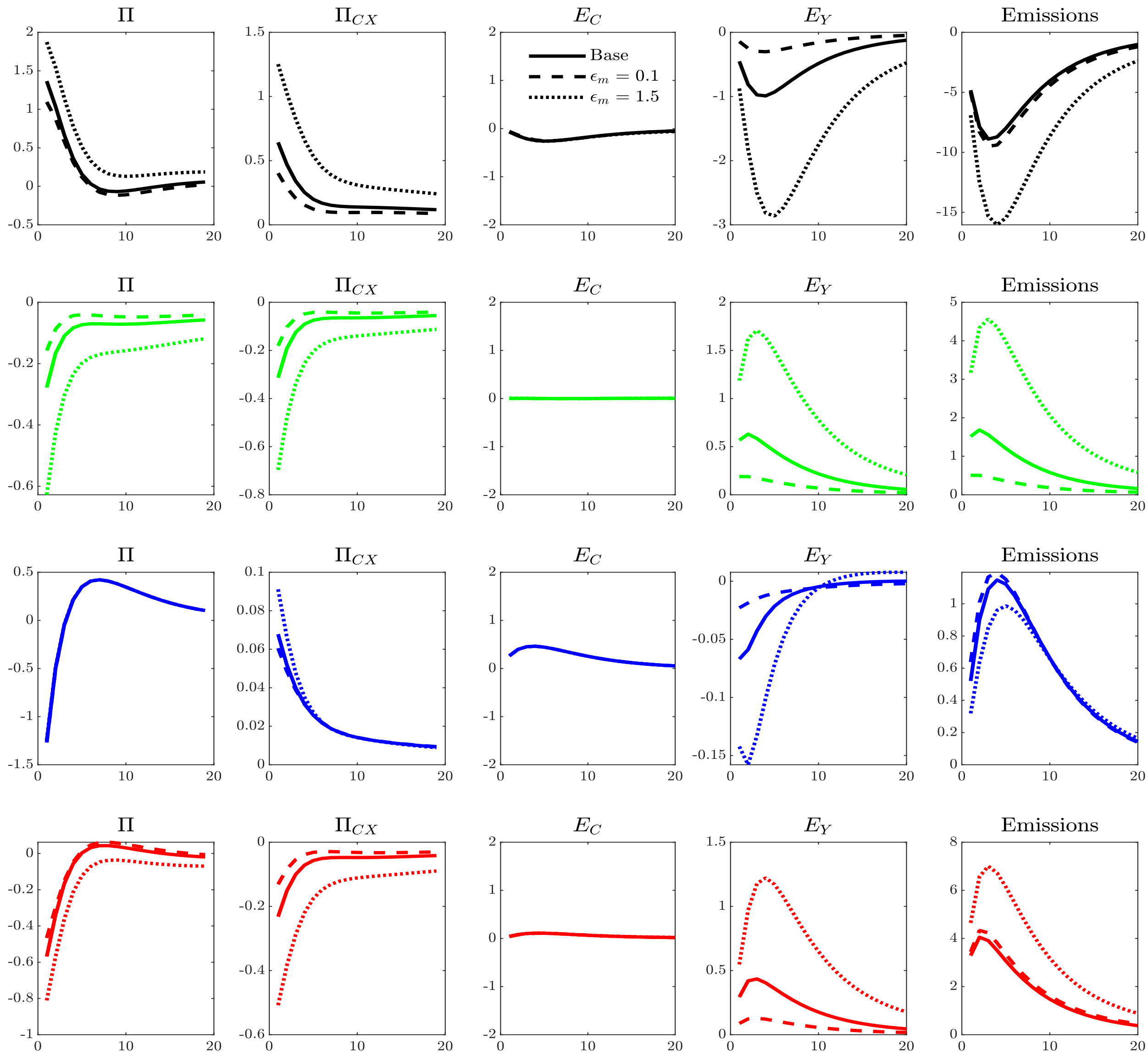
Notes: Impulse responses following a fossil resource price shock (black lines), an energy production subsidy (green lines), an energy consumption subsidy (blue lines), and a carbon subsidy (red lines). Solid lines refer to the baseline (Base) calibration with $\omega_m = 0.92$ and $\omega_c = 0.05$. Dashed lines refer to a calibration with a higher share of energy in production $\omega_m = 0.85$. Dotted lines refer to a calibration with a higher share of energy in consumption $\omega_c = 0.15$. Variables are expressed in percent deviations from steady state values. CPI and core inflation are in percentage point deviations from steady state values. The fossil resource price shock is as in Figure 2. Subsidies follow an AR(1) process of magnitude 1% of GDP with persistence equal to 0.85.

Figure A.2: Robustness: Elasticity of substitution between clean and dirty energy



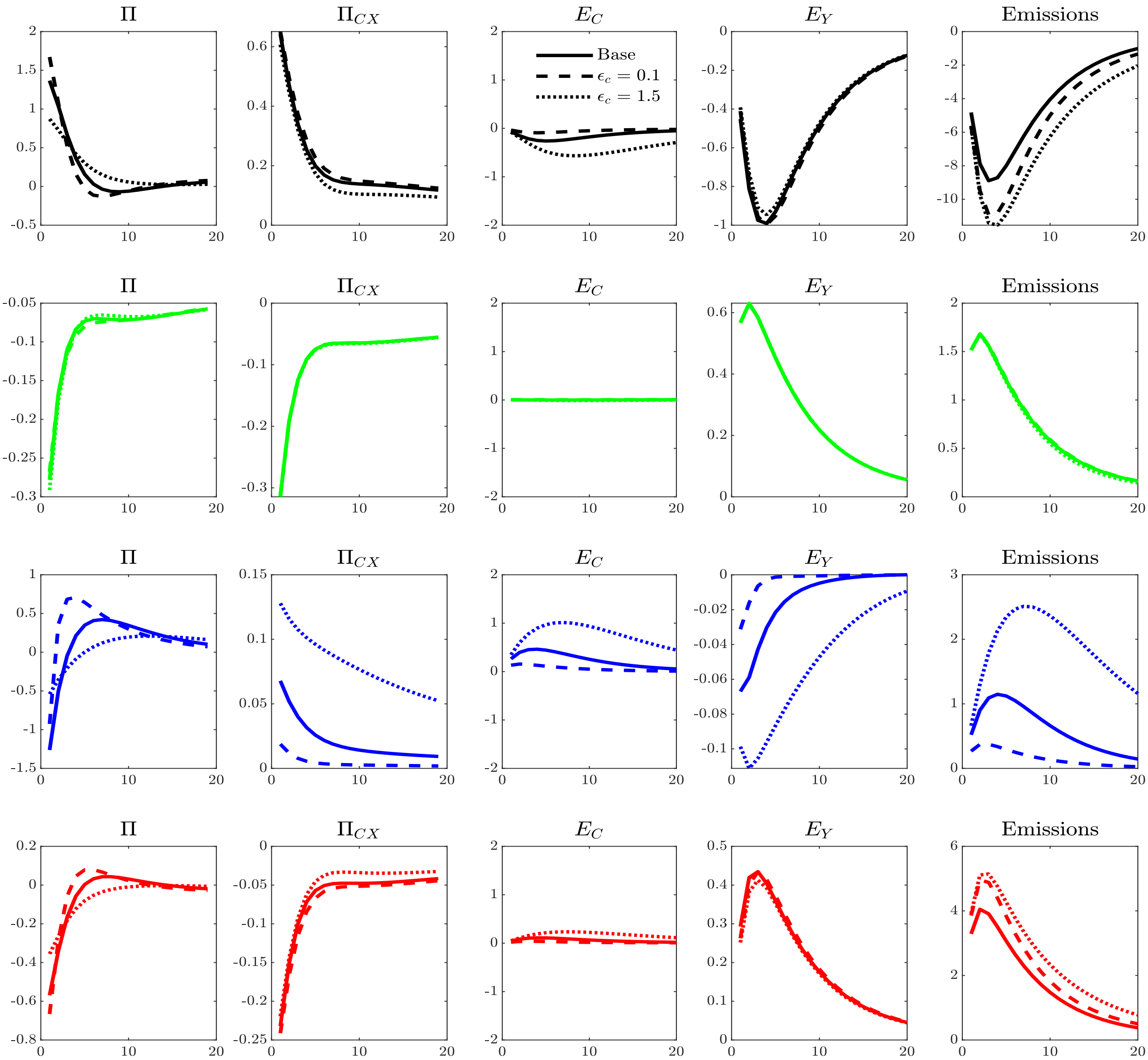
Notes: Impulse responses following a fossil resource price shock (black lines), an energy production subsidy (green lines), an energy consumption subsidy (blue lines), and a carbon subsidy (red lines). Solid lines refer to the baseline (Base) calibration with $\epsilon_e = 1.8$. Dashed lines refer to a calibration with a higher elasticity of substitution between clean and dirty energy $\epsilon_e = 0.3$. Dotted lines refer to a calibration with a lower elasticity $\epsilon_e = 0.9$. Variables are expressed in percent deviations from steady state values. CPI and core inflation are in percentage point deviations from steady state values. The fossil resource price shock is as in Figure 2. Subsidies follow an AR(1) process of magnitude 1% of GDP with persistence equal to 0.85.

Figure A.3: Robustness: Elasticity of substitution between value added and energy



Notes: Impulse responses following a fossil resource price shock (black lines), an energy production subsidy (green lines), an energy consumption subsidy (blue lines), and a carbon subsidy (red lines). Solid lines refer to the baseline (Base) calibration with $\epsilon_m = 0.4$. Dashed lines refer to a calibration with a lower elasticity of substitution between value added and energy $\epsilon_m = 0.1$. Dotted lines refer to a calibration with a higher elasticity $\epsilon_m = 1.5$. Variables are expressed in percent deviations from steady state values. CPI and core inflation are in percentage point deviations from steady state values. The fossil resource price shock is as in Figure 2. Subsidies follow an AR(1) process of magnitude 1% of GDP with persistence equal to 0.85.

Figure A.4: Robustness: Elasticity of substitution between energy and non-energy consumption good



Notes: Impulse responses following a fossil resource price shock (black lines), an energy production subsidy (green lines), an energy consumption subsidy (blue lines), and a carbon subsidy (red lines). Solid lines refer to the baseline (Base) calibration with $\epsilon_c = 0.4$. Dashed lines refer to a calibration with a lower elasticity of substitution between energy and non-energy consumption good $\epsilon_m = 0.1$. Dotted lines refer to a calibration with a higher elasticity $\epsilon_m = 1.5$. Variables are expressed in percent deviations from steady state values. CPI and core inflation are in percentage point deviations from steady state values. The fossil resource price shock is as in Figure 2. Subsidies follow an AR(1) process of magnitude 1% of GDP with persistence equal to 0.85.

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