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Luisa Corrado, Stefano Grassi,
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Luisa Corrado[†], Stefano Grassi[‡], Aldo Paolillo[§] and Francesco Ravazzolo[¶]

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Abstract

This work studies the turbulent confluence of two major events - the COVID-19 pandemic and the Russian invasion of Ukraine - both of which caused significant disruptions in global energy demand and macroeconomic variables. We propose and estimate a two-sector Dynamic Stochastic General Equilibrium model that incorporates both crude and refined energy sources, thus combining together the multifaceted dynamics of the energy sector, where crude elements like oil, coal, and gas are intertwined with other production components. The model describes the transmission of energy shocks through complementarities in production and consumption, as a mechanism that amplifies the fluctuations of the business cycle. We find that the impact of price shocks on oil, coal, and gas accounts for 32% of the increase in the general price level between 2021:Q1 and 2022:Q4, and that oil and gas price shocks contributed most significantly. Finally, we discuss the case in which energy shocks can be Keynesian supply shocks.

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[†] Department of Economics and Finance, University of Rome 'Tor Vergata' and RCEA. Address: Via Columbia 2, Rome (00133), Italy. Email: luisa.corrado@uniroma2.it.

[‡] Department of Economics and Finance, University of Rome 'Tor Vergata' and CREATES. Address: Via Columbia 2, Rome (00133), Italy. Email: stefano.grassi@uniroma2.it.

[§] Department of Economics and Finance, University of Rome 'Tor Vergata'. Address: Via Columbia 2, Rome (00133), Italy. Email: aldo.paolillo@uniroma2.it.

[¶] Department of Data Science and Analytics, BI Norwegian Business School and Faculty of Economics and Management, Free University of Bozen-Bolzano. Address: Piazza Università 1, Bolzano (39100), Italy. Email: francesco.Ravazzolo@unibz.it.

1 Introduction

On 26 August 2022, natural gas in Europe reached a record price of 342 euros (EUR) per megawatt-hour (MWh).[1] Less than a year earlier, the price was only 50 EUR per MWh (EUR/MWh), and from 2010 to 2020, it was between 8 and 32 EUR/MWh. This unprecedented price spike was the result of the Russian invasion of Ukraine, which began on February 24, 2022.[2] Similar massive price increases have also affected other types of energy commodities, including coal and oil, see Figure 1. Two weeks after the beginning of hostilities, oil, coal and gas prices rose by approximately 40%, 130%, and 180%, see Adolfsen et al. (2022).

Inflation in crude energy commodities also led to a significant increase in retail energy prices. For example, the Harmonized Index of Consumer Prices (HICP) of energy products in the Euro area (EA) increased by 37% in 2022 compared to the previous year, see Figure 2. At the same time, the EA economy was recovering from one of the most severe and rapid recessions in its history caused by the COVID-19 pandemic. Specifically, real GDP declined by 11.5% in 2020:Q2, while in 2020:Q3 experienced a rebound of 12.4%. The unusual characteristics of this atypical recession (Cardani et al., 2022 and Ferroni et al., 2022) depend on the closure and reopening of the economy mandated after the outbreak of the COVID-19 pandemic. Recovery dynamics also showed unusual characteristics: while real GDP in 2022:Q3 increased by 2.26% compared to 2019:Q3, at the same time, the HICP of all types of products increased by 12.38%, with the highest inflation rate ever recorded since the introduction of the euro.

The contribution of the paper is to examine the combined effects of the pandemic and energy shocks and to analyze their transmission channels. We propose a closed-economy two-sector Dynamic Stochastic General Equilibrium (DSGE) model with a core sector and an energy sector. In addition to the presence of oil (more established in the literature, see Kim and Loungani, 1992), the model also includes coal and gas to assess the relative importance of these fossil energy sources in determining business cycle fluctuations and price movements, in particular for economies characterized by a production based on an energy mix and not just a single source. On the supply side, the energy sector includes

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[1] As measured by the Dutch TTF Natural Gas Futures, which is Europe's benchmark for natural gas prices. The series is available at `https://tradingeconomics.com/commodity/eu-natural-gas`.

[2] For an assessment of the energy market in time of war, see Pollitt (2022)

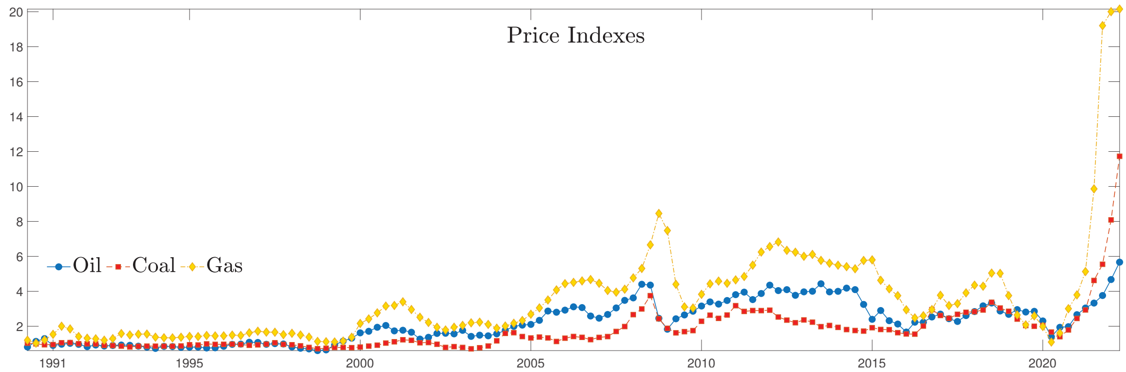

Figure 1: The price indexes of the three main fossil energy sources. Lines represent oil (solid blue line with circles), coal (dashed red line with squares), and natural gas (dash-dotted yellow line with diamonds). The three series are normalized so that they start at the same level. Data sources: oil price is measured as the Spot Crude Oil Price for West Texas Intermediate provided by the Federal Reserve Bank of St. Louis; coal price is measured as the Global price of Coal, Australia, provided by the International Monetary Fund; gas price is measured as the European Union gas price obtained from the International Monetary Fund. See Section 3 for details of the data sources.

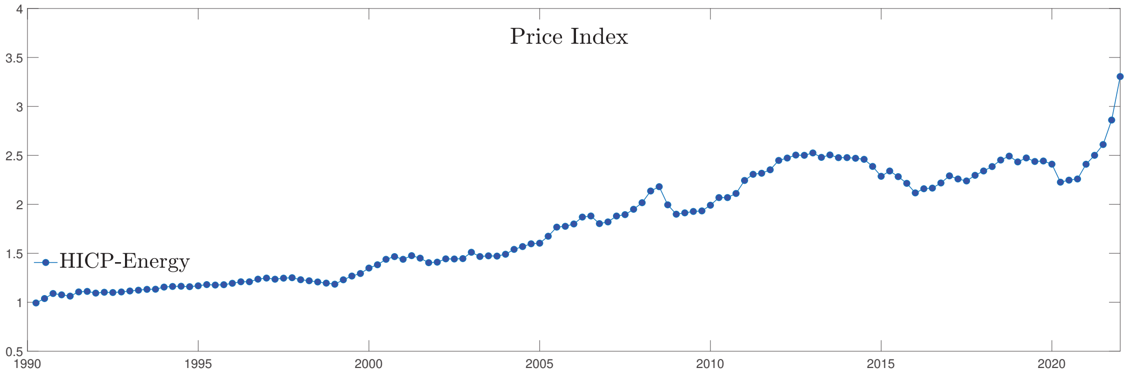

Figure 2: The price index of energy products in the EA. The series is the Harmonized Index of Consumer Prices (HICP) of Energy in the EA, obtained from the Area-Wide Model (AWM) database and from OCSE. See Section 3 for details of the data sources.

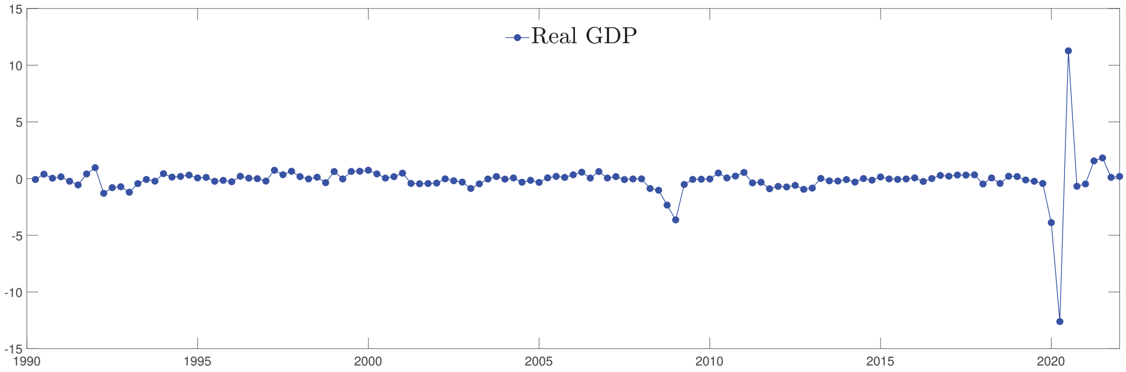

Figure 3: The growth rate of the real GDP in the EA. Data are obtained from the Gross Domestic Product series in the AWM database and from Eurostat. See Section 3 for details of the data sources.

the extraction of crude energy (oil, coal, and gas) and the production of refined energy.[3]

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[3] In the EA, refined energy is produced from primary sources such as coal, crude oil, gas, nuclear energy, hydroelectric energy, and others, and is mainly sold in the domestic market, see Jacquinot et al. (2009) and Donoval et al. (2010). In the EA electricity is an important form of refined energy that represents

On the demand side, we consider the use of refined energy for consumption by households and production by core sector firms.

Since energy is a peculiar component of consumption and production and has limited substitutability with other factors, we assume an unrestricted elasticity of substitution in energy demand by (i) households, (ii) core sector firms, and (iii) energy firms. Various specifications for the degree of substitutability are proposed in the literature, from no substitutability Finn (2000), to a fixed elasticity of substitution equal to one Bodenstein et al. (2007), to an unrestricted elasticity of substitution, Kim and Loungani (1992).[4]

To perform our analysis, we estimate the model using a dataset composed of real and nominal variables for the EA up to 2022:Q4. Our model identifies the contribution of both the recession and rebound shocks in 2020 (pandemic shocks), and the shocks to the price of oil, coal, and gas in 2021-2022 (energy shocks).[5] The oil, coal, and gas markets are highly connected and linked to global economic conditions, see Baumeister et al. (2022) and Bjørnland et al. (2018).

To take into account the potential comovement of the raw energy prices, we first extract a factor from the prices of oil, coal, and gas specified as a latent process in the DSGE model. Then we use this factor together with the global GDP series in a Structural Vector Autoregression (SVAR) model within the DSGE estimation. This approach can be used to explain the potential endogeneity of raw energy prices with respect to global economic activities, see Bjørnland et al. (2018).

We find that while non-energy shocks substantially influence the energy market, determining around 70% of the increase in energy prices between 2021:Q1 and 2022:Q4, the remaining part is accounted for by energy shocks. We also find that energy shocks explain 32% of the increase in the general price level between 2021:Q1 and 2022:Q4. For general and energy price levels, oil and gas are the most important contributors (oil has the largest share of use, and the gas price is subject to the largest shocks), and coal is the least important contributor. Our results also show that cumulative GDP losses between

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25% of the final energy consumption in the residential sector and 33% in the industrial sector in 2021; see Eurostat's Energy Balances, Tables nrg_bal_c and nrg_bal_s. Refined energy comprises various other forms used for domestic and industrial purposes that we also consider in our analysis, specifically: electricity, gas, liquid fuels, solid fuels, heat energy and fuels and lubricants for personal transport equipment.

[4] See Section 2 for additional discussion and Labandeira et al. (2017) for a review of the elasticities of substitution for energy inputs.

[5] We consider only shocks to crude energy, to isolate the effects of commodity price increase in 2021-2022. A broader definition of these shocks could also include shocks to demand and supply of refined energy.

2020:Q4 and 2022:Q4 amount to 2%.

The elasticities of substitution between energy and other goods in the consumption basket of households and in the production function of core sector firms are estimated below one, which indicates the presence of complementarities. Complementarities amplify the effects of energy shocks on the economy since production and consumption become less flexible and both producers and consumers are less able to substitute energy with nonenergy inputs (goods), see Ramey and Vine (2011) and Bachmann et al. (2022). We then perform a counterfactual analysis where we assume different values for the elasticity of substitution in production and consumption and find that the negative effect of energy shocks on GDP increases monotonically when the elasticity of substitution decreases, i.e., when production and consumption functions become less flexible.

We then perform two different counterfactual exercises. First, we analyze the role of the elasticity of substitution of energy in production: we find that after a gas price shock, GDP drops 1.27 times more with our elasticity estimate (0.33) compared to the counterfactual scenario in which the elasticity of substitution is set to one, which corresponds to a higher degree of flexibility in production. In the second exercise, we analyze the role of the elasticity of substitution of energy in consumption: we find that after a gas price shock, with our elasticity estimate (0.50), the composition of household's consumption between energy and non-energy goods changes less than in the counterfactual case where the elasticity of substitution equals one, which corresponds to a higher degree of substitutability between energy and non-energy consumption. As emphasized in the literature, see, among others, Blanchard and Gali (2007), a higher indexation of wages to past prices can exacerbate the negative effects of increases in energy prices. This happens as labor markets react to price shocks by mechanically raising nominal wages, so the upward pressure on prices feeds back into higher labor costs. For this reason, we also analyze how the degree of wage indexation in labor markets affects the transmission of energy shocks. We estimate a high degree of indexation of wages on prices, which amplifies the impact of energy shocks and causes persistent effects on GDP. In the case of a gas price shock, after 20 quarters cumulative GDP losses are approximately three times larger with our estimated wage indexation (0.99) compared to a wage indexation set at a medium level (0.50).

We also discuss whether energy shocks can be considered as Keynesian supply shocks, namely shocks that originate from supply disturbances but are transmitted with the characteristics of demand shocks, see Guerrieri et al. (2022) and Kharroubi and Smets (2023).[6] We find that our estimated rigidities rule out the transmission of energy shocks as Keynesian supply shocks.

Since our structural framework includes a central bank interest rate rule that reacts to inflation, we can study the effects of monetary policy on the transmission of energy shocks, see Bernanke et al. (1997), Leduc and Sill (2004), Blanchard and Gali (2007), Kormilitsina (2011) and Ramey and Vine (2011). Despite the modest share of the energy sector in total output, we find that recent energy shocks have a large impact on inflation. Given this evidence, we evaluate whether the central bank's response to rising inflation amplifies or dampens the transmission of these shocks. We simulate tighter and looser monetary policy responses to inflation by assuming different values for the inflation coefficient in the policy rule.[7] We find that when a gas price shock triggers a more aggressive policy response to inflation, GDP drops twice compared to a looser response. When the central bank does not raise the interest rate after energy shocks, we find that GDP is 1% higher at the end of the sample.

Finally, we analyze the role of fiscal policy in mitigating the impact of energy shocks. We study a fiscal intervention that sterilizes the rise in energy prices faced by households and firms through subsidies that impose a price cap on energy to the pre-2021 level. We find that these subsidies reduce the negative effects of energy shocks on GDP by keeping the demand for energy higher, but the fiscal multipliers of these interventions are below one.

Related literature

The paper is connected to the literature that studies the role of energy in macroeconomic models. Kim and Loungani (1992) analyze the role of energy in a Real Business Cycle (RBC) model, where in a single-sector setup, energy is an input in production and its

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[6] Kharroubi and Smets (2023) analyze the Keynesian feature of energy shocks in a theoretical model with flexible prices and heterogeneous households. They find that energy shocks can have Keynesian effects when income heterogeneity is intermediate and the fraction of credit-constrained households is high.

[7] We change the inflation coefficient from the estimated value of 1.51 to a higher value of 2.50 (aggressive response) and a lower value of 1.25 (looser response). See Section 4 for details.

price follows an exogenous process.[8]

Rotemberg and Woodford (1996) study the role of energy in a model with imperfect competition where oil is used as an input in production, while Finn (2000) analyzes the effects of energy price shocks in a model with perfect competition but with complementarities in production. In this paper, we consider a two-sector model with different kinds of energy sources and with real and nominal rigidities and complementarities in production and consumption. Further refinements to these models have been proposed by Jacquinot et al. (2009), who distinguish between crude and refined energy. Unlike these authors, we include coal and gas in addition to oil as crude inputs in the energy sector, given the large developments in their markets during the time span of our analysis.

Blanchard and Gali (2007) analyze the effects of oil price shocks in a model where oil is used in consumption and production. They analyze the role of various transmission mechanisms, such as wage rigidity, monetary policy, and the weight of oil in production and consumption. Golosov et al. (2014) propose a DSGE model with fossil energy sources and evaluate the optimality of carbon taxes to mitigate a negative environmental externality. Similarly to their paper, we introduce different fossil energy sources, but we concentrate on an empirical analysis using historical data and leave simulations about environmental damage outside the scope of the paper. Dissou and Karnizova (2016) use a rich multi-sectoral economy with coal, oil, and electricity to evaluate the effects of emission caps and emission taxes. Unlike their calibrated model, we do not study carbon emissions, but we focus on energy subsidies as a potential policy to mitigate the effects of the realized shocks.

In this paper, we build and estimate a fully fledged theoretical model to study the propagation of energy shocks, while a large literature uses VAR models to study the macroeconomic effects of recent energy shocks. Casoli et al. (2022) use a Bayesian SVAR to analyze the effect of energy shocks on EA inflation and find correlations between the oil and gas markets. Furthermore, gas shocks and other supply shocks are more important than demand shocks to explain the recent inflationary pressures in the EA. Adolfsen et al. (2024) also study the impact of shocks in the European gas market on EA inflation.

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[8] Using a similar single sector model Dhawan et al. (2010) study the link between energy prices and the volatility of macroeconomic variables during the Great Moderation. For the same historical period, Bjørnland et al. (2018) using a Markov Switching rational expectation New Keynesian model with nominal and real rigidities, analyze the effects of oil price fluctuations on the volatility of macroeconomic variables.

Similarly to our results, they find that gas supply shocks and changes in world economic activity affect energy prices and core sector prices. Using a combination of zero and sign restrictions, Boeck et al. (2023) study the effects of gas price shocks in the EA, focusing on the expectation channel. They find a positive passthrough from gas price shocks to both inflation and inflation expectations. Alessandri and Gazzani (2023) identify gas supply shocks in the EA by constructing a series of external instruments from daily news, and the identified shocks are used in a VAR. They find a stagflationary reaction of the economy to negative gas supply shocks, with the response to gas shocks more gradual but larger than the oil shocks. Moreover, they find a positive impact of gas supply shocks on core prices. Finally, Caldara et al. (2022) and Bruhin et al. (2024) focus on the specific impact of the Russian-Ukrainian War on inflation and economic activity. These contributions leverage on the increase in measures of geopolitical risk and find that the war resulted in non-negligible stagflationary effects on the global (Caldara et al., 2022) and the European (Bruhin et al., 2024) economies. In other recent research, such as Bachmann et al. (2022), large energy shocks from the Russo-Ukrainian War have been analyzed using multi-sectoral models. As in our paper, they show that complementarities can amplify the effects of negative energy supply shocks. Unlike our setup, they focus on Keynesian effects through an input-output model that abstracts from business cycle amplification mechanisms.

The remainder of the paper is organized as follows. Section 2 describes the model. Section 3 discusses the empirical analysis. Section 4 presents the economic results. Finally, Section 5 concludes. Derivations, data description, and further empirical results are reported in the Appendix.

2 Model Description

The economy consists of households, the core sector, the energy sector, the unions, the government, and the central bank, see Figure 4. The crude energy sources are combined by firms in the energy sector and transformed into refined energy. To improve tractability, see Bernanke et al. (1999), firms in both sectors are internally divided into wholesalers (responsible for production processes) and retailers (responsible for selling goods and setting prices). Wholesale firms produce goods according to a production function and transfer the products to retail firms that set prices in the monopolistically competitive final goods

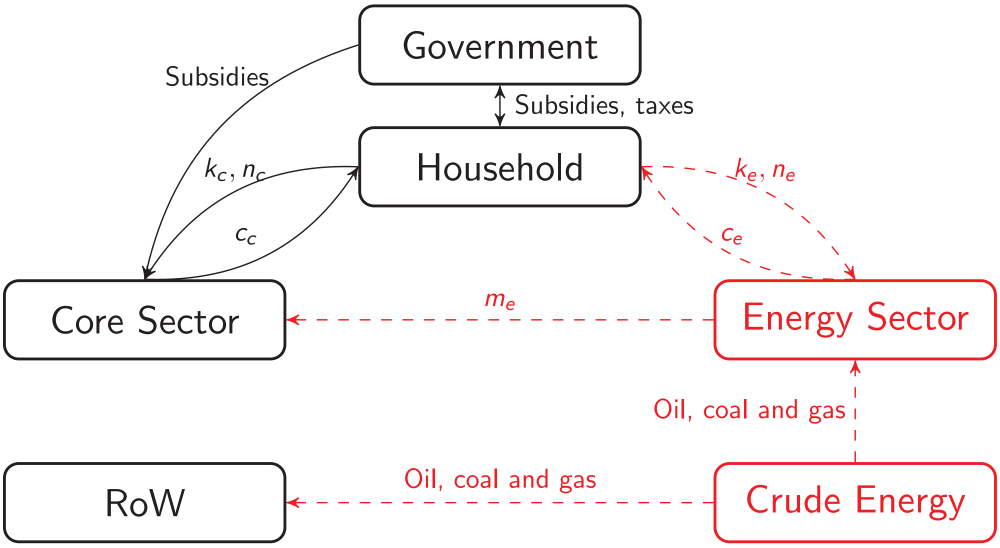

Figure 4: The flowchart of the economy. The ***Core Sector*** *produces general goods;* ***Crude Energy*** *represents the sources of crude energy (oil, coal, and gas) that are refined by the* ***Energy Sector*** *to produce refined energy; the prices of crude energy sources also depend on the* ***Rest of the World*** *(RoW). Arrows represent the flow of the indicated variables.* k_c *and* k_e *represent the capital stocks that are lent by the households to the Core Sector and Energy Sector firms;* n_c *and* n_e *are the hours of work that are supplied by the households and employed by the Core Sector and Energy Sector firms;* c_c *and* c_e *represent the consumption variables demanded by the households to the Core Sector and Energy Sector firms;* m_e *represents the intermediate energy used for production purposes by the Core Sector firms. The arrows connected to the government block represent the subsidies to the price of energy provided to households and firms, and the taxes that the households must pay to finance these subsidies. The Core Sector and the Energy Sector include unions and retail/wholesale branches, which are omitted from the flowchart for brevity. Finally, the central bank is also omitted for convenience.*

markets. The production function of wholesale firms in the core sector takes as input refined energy (m_e), labor (n_c) and capital (k_c), while the production function of wholesale firms in the energy sector takes as input a composite basket of crude energy sources (V_e), labor (n_e) and capital (k_e).

The composite basket of crude energy sources(V_e) is made up of oil (V_o), coal (V_c) and gas (V_g), and the price of these sources also depends on the economic conditions of the rest of the world (RoW). Households consume the core sector good (c_c) and the refined energy good (c_e). The households supply labor (n_c and n_e) and provide capital (k_c and k_e) to wholesale firms in the two sectors. The labor markets include frictions, and unions (not shown in the flow chart for convenience) act as intermediaries between households and wholesale firms introducing contractual wage stickiness in both sectors, see Smets and Wouters (2007) and Iacoviello and Neri (2010). Finally, the government is responsible for imposing taxes and subsidies on households and firms, and the central bank is responsible for the monetary policy. The core sector will be denoted as the 'c' Sector ($\mathcal{S}_c$), while the energy sector will be indicated as the 'e' Sector ($\mathcal{S}_e$).

Energy Sector

Energy firms supply refined energy ($Y_{e,t}$) and they are divided into wholesale and retail branches. Wholesale energy firms rent capital ($k_{e,t}$) from households, demand labor ($n_{e,t}$) from unions, and employ crude energy sources (oil, $V_{o,t}$, gas, $V_{g,t}$, and coal, $V_{c,t}$) taking the input prices (the real wage rate $w_{c,t}$, the real capital rental rate $r_{k_c,t}$) and the prices of crude energy sources ($p_{o,t}$, $p_{g,t}$ and $p_{c,t}$) as given. These prices are expressed in relative terms by dividing the nominal prices ($P_{o,t}$, $P_{g,t}$ and $P_{c,t}$) by the price of energy in the final goods market ($P_{e,t}$) and are given by $p_{o,t} = \frac{P_{o,t}}{P_{e,t}}$, $p_{c,t} = \frac{P_{c,t}}{P_{e,t}}$ and $p_{g,t} = \frac{P_{g,t}}{P_{e,t}}$, for oil, coal, and gas, respectively. Capital ($k_{e,t}$) is also used to refine crude energy sources. Wholesale energy firms sell refined energy at a wholesale price $P^w_{e,t}$, and we denote the markup between this wholesale price and the price of the final goods as $X_{e,t} = \frac{P_{e,t}}{P^w_{e,t}}$.

The optimization problem, writing the profit function in real terms dividing it by $P_{e,t}$, is:

$$\max \frac{Y_{e,t}}{X_{e,t}} - w_{e,t}n_{e,t} - r_{k_e,t}u_{k_e,t}k_{e,t-1} - p_{o,t}V_{o,t} - p_{g,t}V_{g,t} - p_{c,t}V_{c,t}, \tag{1}$$

subject to the production function:

$$Y_{e,t} = a_{z_e,t}a^{ss}_{z_e}\left(n_{e,t}\right)^{1-\alpha_e}\left[u_{k_e,t}k^{\omega_{k_e}}_{e,t-1}V^{1-\omega_{k_e}}_{e,t}\right]^{\alpha_e}, \tag{2}$$

where, similarly to Golosov et al. (2014), the composite basket of crude energy ($V_{e,t}$) is a Constant Elasticity of Substitution (CES) aggregator of the three crude energy sources:

$$V_{e,t} = \left[a_{V_o,t}\omega_o^{\frac{1}{\sigma_v}}V_{o,t}^{\frac{\sigma_v-1}{\sigma_v}} + a_{V_g,t}\omega_g^{\frac{1}{\sigma_v}}V_{g,t}^{\frac{\sigma_v-1}{\sigma_v}} + a_{V_c,t}(1-\omega_o-\omega_g)^{\frac{1}{\sigma_v}}V_{c,t}^{\frac{\sigma_v-1}{\sigma_v}}\right]^{\frac{\sigma_v}{\sigma_v-1}}. \tag{3}$$

In eq. (2), the variable $a_{z_e,t}$ is the productivity in the energy sector, which is multiplied by the parameter $a^{ss}_{z_e}$ that scales the size of the energy sector (Y_e) in the steady state, see Appendix B. The capital share parameter α_e determines the cost share of capital and crude energy relative to labor in the production of refined energy, and the parameter ω_{k_e} determines the cost share of capital relative to crude energy. In eq. (3), the parameter σ_v is the elasticity of substitution between oil, coal, and gas, while the parameters ω_o and ω_g determine the steady-state values of these energy inputs. The variables $a_{V_o,t}$, $a_{V_g,t}$, and $a_{V_c,t}$ are exogenous productivities of crude energy sources that influence the demand for these inputs by the energy sector. Given the CES aggregator in eq. (3), we define the price index of crude energy as:

$$p_{v,t} = \left[\omega_o p_{o,t}^{1-\sigma_v} + \omega_g p_{g,t}^{1-\sigma_v} + (1-\omega_o-\omega_c) p_{c,t}^{1-\sigma_v}\right]^{\frac{1}{1-\sigma_v}} . \tag{4}$$

The solution to the profit maximization problem faced by the energy firms in eq. (1) subject to eq. (2) and eq. (3) gives the optimal demand schedules of the input factors in the energy sector, see Appendix A.

Retailers in the energy sector buy wholesale goods $Y_{e,t}$ at a price $P_{e,t}^{w}$ and differentiate them at no cost into a continuum of varieties that have a constant elasticity of substitution equal to ϵ_{π_e}. The resulting demand for each variety j of the final product is given by $Y_{e,t}(j) = \left(\frac{P_{e,t}(j)}{P_{e,t}}\right)^{-\epsilon_{\pi_e}} Y_{e,t}$. Retailers face quadratic adjustment costs *à la* Rotemberg in the retail price $P_{e,t}(j)$, and these adjustment costs depend on the inflation rate in the previous quarter, with relative weight given by the indexation parameter ι_{π_e}. Adjustment costs ($\Xi_{\pi_e,t}$) generate price stickiness and are given by:

$$\Xi_{\pi_e,t} = \frac{\eta_{\pi_e}}{2}\left(\frac{P_{e,t}(j)}{P_{e,t-1}(j)} - \pi_{e,t-1}^{\iota_{\pi_e}}\right)^2 Y_{e,t},$$

which shows that deviations of the prices of individual varieties $\left(\frac{P_{e,t}(j)}{P_{e,t-1}(j)}\right)$ from last quarter's inflation ($\pi_{e,t-1}^{\iota_{\pi_e}}$) are penalized, depending on the rigidity parameters η_{π_e}. This price setting problem is standard, see Appendix A.

Concerning the supply of crude energy sources, to account for their comovement, we assume that their prices depend on a common unobserved factor ($p_{f,t}$) plus idiosyncratic components ($a_{p_o,t}$, $a_{p_g,t}$ and $a_{p_c,t}$):

$$\begin{bmatrix} p_{o,t} \\ p_{g,t} \\ p_{c,t} \end{bmatrix} = \begin{bmatrix} \lambda_o \\ \lambda_g \\ \lambda_c \end{bmatrix} p_{f,t} + \begin{bmatrix} a_{p_o,t} \\ a_{p_g,t} \\ a_{p_c,t} \end{bmatrix}, \tag{5}$$

where λ_o, λ_g and λ_c are the loadings to the common factor.[9] We assume that the idiosyn-

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[9] These loadings scale the steady state of the common factor (p_f^{ss}) to ensure that the steady state of the prices (p_o^{ss}, p_g^{ss} and p_c^{ss}) are equal to the desired targets, namely $\lambda_o = p_o^{ss}/p_f^{ss}$, $\lambda_g = p_g^{ss}/p_f^{ss}$ and $\lambda_c = p_c^{ss}/p_f^{ss}$, see Appendix B.

cratic components are autoregressive (AR) processes, namely:

$$
\begin{aligned}
a_{p_o,t} &= \rho_{p_o} a_{p_o,t-1} + \varepsilon_{p_o,t}, \\
a_{p_g,t} &= \rho_{p_g} a_{p_g,t-1} + \varepsilon_{p_g,t}, \\
a_{p_c,t} &= \rho_{p_c} a_{p_c,t-1} + \varepsilon_{p_c,t},
\end{aligned}
\tag{6}
$$

where, ρ_{p_o}, ρ_{p_g} and ρ_{p_c} are persistence parameters and $\varepsilon_{p_o,t}$, $\varepsilon_{p_g,t}$ and $\varepsilon_{p_c,t}$ are Gaussian white noises, with standard deviations equal to σ_{p_o}, σ_{p_g} and σ_{p_c}. To account for the endogeneity of the price of crude energy to global economic conditions, we assume that the common factor $(p_{f,t})$ is determined in a SVAR with global GDP (GDP_t^{W}):[10]

$$
\boldsymbol{A}_0 \begin{bmatrix} \Delta \log\left(GDP_t^{\mathrm{W}}\right) \\ \log\left(p_{f,t}\right) \end{bmatrix} = \boldsymbol{c} + \sum_{q=1}^{2} \boldsymbol{A}_q \begin{bmatrix} \Delta \log\left(GDP_{t-q}^{\mathrm{W}}\right) \\ \log\left(p_{f,t-q}\right) \end{bmatrix} + \begin{bmatrix} \varepsilon_{W,t} \\ \varepsilon_{p_f,t} \end{bmatrix}, \tag{7}
$$

where $\boldsymbol{A}_0$, $\boldsymbol{A}_1$, $\boldsymbol{A}_2$ are coefficient matrices, $\boldsymbol{c}$ is the vector of constants and $\varepsilon_{W,t}$ and $\varepsilon_{p_f,t}$ the Gaussian white noise shocks to global GDP and crude energy price, with standard deviation equal to σ_{p_f} and σ_W. As in Bjørnland et al. (2018) and similarly to Kilian (2009) we assume two lags in the SVAR and $\boldsymbol{A}_0$ a lower triangular matrix, implying a lagged response of global GDP to the crude energy price shock, whereas crude energy prices can respond contemporaneously to a global GDP shock.[11] The SVAR block is simultaneously estimated with the other equations of the DSGE model and allows us to directly obtain the common factor driving the crude energy prices.[12] A SVAR with only global activity and the common factor for crude energy prices excludes an endogenous effect of the activity of the EA; this is reasonable given that the EA represents a modest share of the global economy.[13]

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[10] Exogenous oil supply has been considered by Leduc and Sill (2004), Blanchard and Gali (2007) and Bodenstein et al. (2011), among others. The gains from endogenizing the price of oil have been stressed by Kilian (2009) and Nakov and Pescatori (2010), among others.

[11] Note that differently from Bjørnland et al. (2018) and Kilian (2009) we use a common factor for the price of crude energy and not the price of oil. Also note that similar to these authors we insert the global GDP in log differences and the energy price in logs.

[12] Technically, the parameters of the VAR in eq. (7) are estimated together with the other model parameters with the Metropolis-Hastings algorithm and the common factor $p_{f,t}$ is extracted as a latent variable with the Kalman smoother.

[13] Precisely, 12% as a share of world GDP in PPP for the year 2022, according to the ECB. Source: `https://www.ecb.europa.eu/mopo/eaec/html/index.en.html`

Core Sector

The core sector is divided into wholesale and retail branches. Wholesale core sector firms operate the production technology and charge flexible wholesale prices to retail core sector firms. Wholesale firms rent raw capital ($k_{c,t}$) from households, demand labor ($n_{c,t}$) from unions, and employ intermediate energy goods ($m_{e,t}$) taking the input prices (the real wage rate $w_{c,t}$, the real rental rate of raw capital $r_{k_c,t}$, and the relative price of the energy goods to the core sector goods, $p_{e,t} = P_{e,t}/P_{c,t}$) as given to maximize their profits. Wholesale core firms sell goods at a wholesale price $P^w_{c,t}$, and we denote the markup between this wholesale price and the final price as $X_{c,t} = \frac{P_{c,t}}{P^w_{c,t}}$. The resulting optimization problem (writing the profit function in real terms by dividing it by $P_{c,t}$) is:

$$\max \frac{Y_{c,t}}{X_{c,t}} - w_{c,t}n_{c,t} - r_{k_c,t}u_{k_c,t}k_{c,t-1} - p_{e,t}m_{e,t}, \tag{8}$$

subject to the production function:

$$Y_{c,t} = a_{z_c,t}\left(n_{c,t}\right)^{1-\alpha_c}\left(u_{k_c,t}\bar{k}_{c,t}\right)^{\alpha_c}, \tag{9}$$

where $\bar{k}_{c,t}$ is capital used in the core sector, which is a CES function[14] of raw capital and energy, with an elasticity of substitution equal to σ_{k_c}. The expression for $\bar{k}_{c,t}$ is the following:

$$\bar{k}_{c,t} = \left[\omega_{k_c}^{\frac{1}{\sigma_{k_c}}} k_{c,t-1}^{\frac{\sigma_{k_c}-1}{\sigma_{k_c}}} + \left(1-\omega_{k_c}\right)^{\frac{1}{\sigma_{k_c}}} m_{e,t}^{\frac{\sigma_{k_c}-1}{\sigma_{k_c}}}\right]^{\frac{\sigma_{k_c}}{\sigma_{k_c}-1}}, \tag{10}$$

where ω_{k_c} is a parameter used to pin down the steady-state value for the share of expenditure in raw capital and energy over the total costs of capital in production. The CES function, which is also used to define the households' consumption bundle (see the next subsection), nests the extreme cases of perfect substitutability ($\sigma_{k_c} \to +\infty$), Cobb-Douglas function ($\sigma_{k_c} \to 1$), and perfect complementarity ($\sigma_{k_c} \to 0$). To let the data speak, we estimate this parameter (Section 3). The solution to the profit maximization

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[14] Cobb-Douglas functions (implying an elasticity of substitution equal to one) have been proposed for instance by Bodenstein et al. (2007), Blanchard and Gali (2007), Bjørnland et al. (2018), Argentiero et al. (2018); CES functions (implying an unrestricted elasticity of substitution) have been used by Kim and Loungani (1992), Jacquinot et al. (2009), Dhawan et al. (2010), Bodenstein et al. (2011), Bodenstein and Guerrieri (2011), Natal (2012), Balke and Brown (2018) among others; functions with a fixed energy requirement tied to the level of production (analog to Leontief function, implying an elasticity of substitution equal to zero) have been proposed by Finn (2000), Leduc and Sill (2004), Kormilitsina (2011), Dissou and Karnizova (2016).

problem faced by the core firms in eq. (8) subject to eq. (9) and eq. (10) gives the optimal demand schedules of the input factors in the core sector, see Appendix A.

Similarly to the energy sector, retailers in the core sector buy wholesale goods $Y_{c,t}$ at a price $P^{w}_{c,t}$ and differentiate them at no cost into a continuum of varieties with a constant elasticity of substitution equal to ϵ_{π_c}. The resulting demand for each variety j of the final good is then given by $Y_{c,t}(j) = \left(\frac{P_{c,t}(j)}{P_{c,t}}\right)^{-\epsilon_{\pi_c}} Y_{c,t}$. Retailers face quadratic adjustment costs *à la* Rotemberg in the retail price $P_{c,t}(j)$, and these adjustment costs depend on the inflation rate in the previous quarter, with relative weight given by the indexation parameter ι_{π_c}. The adjustment costs ($\Xi_{\pi_c,t}$) are given by:

$$\Xi_{\pi_c,t} = \frac{\eta_{\pi_c}}{2}\left(\frac{P_{c,t}(j)}{P_{c,t-1}(j)} - \pi_{c,t-1}^{\iota_{\pi_c}}\right)^2 Y_{c,t},$$

which shows that deviations of the prices of individual varieties $\left(\frac{P_{c,t}(j)}{P_{c,t-1}(j)}\right)$ from the inflation in the previous quarter ($\pi_{c,t-1}^{\iota_{\pi_c}}$) are penalized, depending on the rigidity parameters η_{π_c}. The complete maximization problem and the resulting Phillips curve are reported in Appendix A.

Households

At each time t, the households choose the basket of core and energy consumption ($\bar{c}_t$), the hours worked in both sectors ($n_{c,t}$ and $n_{e,t}$), the investment in the capital stocks of both sectors ($i_{c,t}$ and $i_{e,t}$), the fractions of capital to be used in production ($u_{k_c,t}$ and $u_{k_e,t}$), and the bonds to hold (b_t) to maximize lifetime utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} (\beta)^t a_{\zeta,t}\left[\frac{1-h}{1-\beta h}\log(\bar{c}_t - h\bar{c}_{t-1}) - a_{\varphi,t}\varphi^c \frac{n_{c,t}^{1+\nu_c}}{1+\nu_c} - a_{\varphi,t}\varphi^e \frac{n_{e,t}^{1+\nu_e}}{1+\nu_e}\right]. \tag{11}$$

The expression in (11) describes the discounted flow of utility that comes from consumption, less the disutility of supplying labor to both sectors. The parameter β is the intertemporal discount rate and $a_{\zeta,t}$ is the shock of the discount factor that reflects changes in the degree of patience of households. The parameters ν_c and ν_e determine the curvature of the disutility of labor and measure the elasticity of labor supply to the wage rate. The term $a_{\varphi,t}$ is the labor supply shock (e.g., new social insurance programs) that can increase or decrease the hours worked. Weights φ^c and φ^e are scale coefficients that impose steady-state values for hours worked that are consistent with historical averages. The term h is the external habits parameter, that increases the persistence of consumption over time. The consumption basket $\bar{c}_t$ is a CES function that includes the consumption of the good of the core sector ($c_{c,t}$) and the good of the energy sector ($c_{e,t}$), and is given by:

$$\bar{c}_t = \left[\omega_{c_c}^{\frac{1}{\sigma_c}} c_{c,t}^{\frac{\sigma_c-1}{\sigma_c}} + a_{j,t}^{\frac{1}{\sigma_c}} \left(1-\omega_{c_c}\right)^{\frac{1}{\sigma_c}} c_{e,t}^{\frac{\sigma_c-1}{\sigma_c}} \right]^{\frac{\sigma_c}{\sigma_c-1}}. \tag{12}$$

In eq. (12), the parameter σ_c is the elasticity of substitution between consumption of core sector goods and energy sector goods. The parameter ω_{c_c} controls the steady-state ratio between energy and non-energy expenditure by households. The variable $a_{j,t}$ is a taste shifter reflecting changes in the relative importance of energy and non-energy goods in consumption, which increases or decreases exogenously the demand for energy by households. We refer to this shock as the *'energy demand'* shock.

The households must satisfy the following budget constraint while maximizing utility:

$$\begin{aligned} c_{c,t} + p_{e,t}c_{e,t} + \frac{i_{c,t}}{a_{k,t}} + p_{e,t}\frac{i_{e,t}}{a_{k,t}} + b_t = & \frac{R_{t-1}b_{t-1}}{\pi_{c,t}} + \frac{w_{c,t}n_{c,t}}{X_{w_c,t}} + p_{e,t}\frac{w_{e,t}n_{e,t}}{X_{w_e,t}} \\ & + r_{k_c,t}u_{k_c,t}k_{c,t-1} + p_{e,t}r_{k_e,t}u_{k_e,t}k_{e,t-1} \\ & + \Pi_t - \frac{\Psi_t}{a_{k,t}} + p_{e,t}p_{v,t}V_{e,t}, \end{aligned} \tag{13}$$

which is expressed in real terms by using the relative price of energy sector goods to core sector goods ($p_{e,t} = P_{e,t}/P_{c,t}$). In the budget constraint, variables $r_{k_c,t}$ and $r_{k_e,t}$ are the real rental rates of capital in both sectors, while $w_{c,t}$ and $w_{e,t}$ represent the real wages. In eq. (13), the elements on the right-hand side (r.h.s.) represent the net source of funds coming from wage income in the core sector ($\frac{w_{c,t}n_{c,t}}{X_{w_c,t}}$) and in the energy sector ($p_{e,t}\frac{w_{e,t}n_{e,t}}{X_{w_e,t}}$), returns on capital rented to core firms ($r_{k_c,t}u_{k_c,t}k_{c,t-1}$) and energy sector firms ($p_{e,t}r_{k_e,t}u_{k_e,t}k_{e,t-1}$), from endowment of natural resources ($p_{e,t}p_{v,t}V_{e,t}$), and from liquidating assets represented by expiring bonds (b_{t-1}). Bonds are issued in nominal units in terms of the numeraire (the core good) and carry a risk-free gross yield equal to R_t, so the real gross returns are given by $R_{t-1}b_{t-1}/\pi_{c,t}$, where $\pi_{c,t}$ denotes the inflation rate of the numeraire ($P_{c,t}/P_{c,t-1}$). The terms $X_{w_c,t}$ and $X_{w_e,t}$ are the wage markups, representing the wedge between the wage paid by the wholesale firms and the wage received by the households, which are collected by labor unions, who are responsible for enforcing monopolistic competition in the labor market. In the budget constraint, Π_t collects all the profits from retailers and labor unions; these profits are taken as a lump sum by households, and their expression is provided in Appendix A. The variable Ψ_t collects investment adjustment costs and capacity adjustment costs, see Appendix A. The elements on the left-hand side (l.h.s.) show the allocation of available funds between non-energy and energy consumption ($c_{c,t}$ and $c_{e,t}$), investment in the core ($i_{c,t}$) and energy sector ($i_{e,t}$) capital, and new bonds (b_t). The net investment in the core sector ($i_{c,t}$) and in the energy sector ($i_{e,t}$) are equal to the difference between the new amount of capital minus the amount of capital in the previous period, net of depreciation:

$$i_{c,t} = k_{c,t} - (1 - \delta_{k_c})\, k_{c,t-1}, \qquad \text{and} \qquad i_{e,t} = k_{e,t} - (1 - \delta_{k_e})\, k_{e,t-1}, \tag{14}$$

where the parameters δ_{k_c} and δ_{k_e} are the capital depreciation rates for the core and energy sectors. Finally, the variable $a_{k,t}$ is the marginal productivity of the investment shock, which makes investment goods more or less costly than consumption goods, see Justiniano et al. (2010). The solution to the utility maximization problem of households in eq. (11) subject to eqs. (12), (13) and (14) gives the optimal demand for goods from the core and energy sector, the optimal demand for bonds, and the optimal supply of labor and capital to both sectors, see Appendix A.

Unions

Unions buy homogeneous labor services from households and differentiate them at no cost. Differentiated labor varieties $n_{i,t}(j)$, where j indicates the variety and i the sector, are then aggregated into CES composites and sold to wholesale firms. Labor unions face the labor demand schedules of firms in both sectors $n_{i,t}(j) = \left(\frac{W_{i,t}(j)}{W_{i,t}}\right)^{-\epsilon_w} n_{i,t}$, $i \in \{c, e\}$, and pay quadratic adjustment costs *à la* Rotemberg for wage changes. The quadratic adjustment costs depend on inflation in the previous quarter weighted by the indexation parameter ι_w. The expressions for these adjustment costs are:

$$\Xi_{w_i,t} = \frac{\eta_w}{2}\left(\frac{W_{i,t}(j)}{W_{i,t-1}(h)} - \pi_{i,t-1}^{\iota_w}\right)^2 w_{i,t} n_{i,t}, \qquad i \in \{c, e\},$$

where η_w determines the degree of wage rigidity. The solution to this optimization problem gives the wage Phillips curves for the two sectors, see Appendix A.

Monetary Policy

The central bank sets the interest rate according to the Taylor rule:

$$R_t = R_{t-1}^{r_R} R_{ss}^{1-r_R} \pi_t^{(1-r_R)r_\pi} \left(\frac{GDP_t}{GDP_{t-1}} \right)^{(1-r_R)r_Y} (a_{r,t}) \exp(\varepsilon_{e,t}). \tag{15}$$

In eq. (15), R_{ss} is the steady-state gross interest rate, $\varepsilon_{e,t}$ is a Gaussian white noise shock that captures momentary deviations from the desired target of monetary policy, and $a_{r,t}$ is an autocorrelated process that reflects more persistent shifts in monetary policy and is given by:

$$\log(a_{r,t}) = \rho_r \log(a_{r,t-1}) + \varepsilon_{r,t},$$

where ρ_r is the persistence parameter and $\varepsilon_{r,t}$ is a Gaussian white noise with a standard deviation equal to σ_r. Eq. (15) shows that the central bank responds to inflation and GDP movements with weights r_π and r_Y, and with a degree of inertia equal to r_R.

We define gross domestic product (GDP_t) in eq. (15) as the sum of production in the two sectors ($Y_{c,t}$ and $Y_{e,t}$), minus the intermediate inputs used (refined energy $m_{e,t}$ by the core sector and crude energy $V_{e,t}$ by the energy sector):

$$GDP_t = Y_{c,t} - p_{e,t} m_{e,t} + p_{e,t} \left(Y_{e,t} - p_{v,t} V_{e,t} \right).$$

The general inflation rate (π_t) is the weighted average between core inflation ($\pi_{c,t} = P_{c,t}/P_{c,t-1}$) and inflation of energy products ($\pi_{e,t} = P_{e,t}/P_{e,t-1}$), with weights equal to the value added shares in the two sectors:

$$\pi_t = \pi_{c,t}^{s_{c,t}} \pi_{e,t}^{1-s_{c,t}}, \tag{16}$$

where $s_{c,t}$ is the share of value added of the core sector over GDP at time t, given by $s_{c,t} = \left(Y_{c,t} - p_{e,t} m_{e,t} \right) / GDP_t$.

Aggregation and Equilibrium

Aggregate consumption and aggregate investment are also defined here for convenience:

$$c_t = c_{c,t} + p_{e,t} c_{e,t}, \qquad\qquad i_t = i_{c,t} + p_{e,t} i_{e,t}.$$

The evolution of the relative price of $\mathcal{S}_e$ is linked to the inflation rates in the two sectors:

$$\frac{p_{e,t}}{p_{e,t-1}} = \frac{P_{e,t}/P_{c,t}}{P_{e,t-1}/P_{c,t-1}} = \frac{\pi_{e,t}}{\pi_{c,t}}.$$

The evolution of the relative prices of oil, coal and gas ($p_{o,t}$, $p_{c,t}$ and $p_{g,t}$) are linked to the inflation rates of their nominal prices, π_t^o, π_t^c and π_t^g:

$$\frac{p_{o,t}}{p_{o,t-1}} = \frac{P_{o,t}/P_{e,t}}{P_{o,t-1}/P_{e,t-1}} = \frac{\pi_t^o}{\pi_{e,t}}, \qquad \frac{p_{c,t}}{p_{c,t-1}} = \frac{\pi_t^c}{\pi_{e,t}}, \qquad \frac{p_{g,t}}{p_{g,t-1}} = \frac{\pi_t^g}{\pi_{e,t}}.$$

The resource constraint for $\mathcal{S}_c$ ensures that the amounts of consumption and investment are equal to production net of losses due to adjustment costs:[15]

$$c_{c,t} + i_{c,t} + p_{e,t} i_{e,t} = Y_{c,t} - \Psi_t - \Xi_{c,t}. \tag{17}$$

The term Ψ_t collects all the real adjustment costs related to capital and capacity utilization (see households' subsection), while $\Xi_{c,t}$ contains the nominal adjustment costs in the core sector (their expressions are given in Appendix A).

The resource constraint for $\mathcal{S}_e$ ensures that the amount of energy used by households ($c_{e,t}$) and by core sector firms ($m_{e,t}$) is equal to the amount of energy produced by energy sector firms ($Y_{e,t}$), net of losses due to nominal adjustment costs ($\Xi_{e,t}$):

$$c_{e,t} + m_{e,t} = Y_{e,t} - \Xi_{e,t}. \tag{18}$$

As in Smets and Wouters (2003), we define employment as an auxiliary variable (l_t) that responds sluggishly (depending on a rigidity parameter θ_l) to changes in hours worked, according to the formula:

$$l_t - l_{t-1} = \mathbb{E}_t l_{t+1} - l_t + \left[\frac{(1-\theta_l)(1-\beta\theta_l)}{\theta_l}\right](n_{c,t} + n_{e,t} - l_t).$$

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[15] Note that investments in the core and energy sector ($i_{c,t}$ and $i_{s,t}$) appear in the resource constraint of the core sector. This is because we assume that investment goods are created from core sector goods ($Y_{c,t}$) and not from refined energy ($Y_{e,t}$). See Iacoviello and Neri (2010) for a similar choice in a model with a core sector and a housing sector. Note that real adjustment costs related to capital and capacity utilization (Ψ_t) appear accordingly in the resource constraint of the core sector.

This variable is needed to estimate the model, as for the EA a measure of aggregate hours worked is not available, while employment is available, see Section 3.

Finally, we define aggregate wage inflation (ω_t) as the average between inflation in both sectors ($\mathcal{S}_c$ and $\mathcal{S}_e$), weighted by the ratio of hours worked in steady state (n_c^{ss} and n_e^{ss}):

$$\omega_t = \frac{n_c^{ss}}{n_c^{ss}+n_e^{ss}}\omega_{c,t} + \frac{n_e^{ss}}{n_c^{ss}+n_e^{ss}}\omega_{e,t}.$$

Exogenous Processes

The remaining exogenous variables are assumed to be AR processes that describe the evolution of: the discount factor shock ($a_{\zeta,t}$); the energy demand shock ($a_{j,t}$); the labor disutility shock ($a_{\varphi,t}$); the productivity of crude oil, coal and natural gas ($a_{V_o,t}$, $a_{V_c,t}$, $a_{V_g,t}$); the marginal productivity of investment ($a_{k,t}$); the core sector productivity ($a_{z_c,t}$); and the energy sector productivity ($a_{z_e,t}$). More in detail:

$$\begin{aligned}
&\log(a_{\zeta,t}) = \rho_\zeta \log(a_{\zeta,t-1}) + \varepsilon_{\zeta,t}, && \log(a_{j,t}) = \rho_j \log(a_{j,t-1}) + \varepsilon_{j,t},\\
&\log(a_{\varphi,t}) = \rho_\varphi \log(a_{\varphi,t-1}) + \varepsilon_{\varphi,t}, && \log(a_{V_o,t}) = \rho_{V_o} \log(a_{V_o,t-1}) + \varepsilon_{V_o,t},\\
&\log(a_{V_c,t}) = \rho_{V_c} \log(a_{V_c,t-1}) + \varepsilon_{V_c,t}, && \log\left(a_{V_g,t}\right) = \rho_{V_g} \log\left(a_{V_g,t-1}\right) + \varepsilon_{V_g,t},\\
&\log(a_{k,t}) = \rho_k \log(a_{k,t-1}) + \varepsilon_{k,t}, && \log(a_{z_c,t}) = \rho_{z_c} \log(a_{z_c,t-1}) + \varepsilon_{z_c,t},\\
&\log(a_{z_e,t}) = \rho_{z_e} \log(a_{z_e,t-1}) + \varepsilon_{z_e,t}.
\end{aligned}$$

The variables $\varepsilon_{\zeta,t}$, $\varepsilon_{j,t}$, $\varepsilon_{\varphi,t}$, $\varepsilon_{V_o,t}$, $\varepsilon_{V_c,t}$, $\varepsilon_{V_g,t}$, $\varepsilon_{k,t}$, $\varepsilon_{z_c,t}$ and $\varepsilon_{z_e,t}$ are Gaussian white noises with standard deviations equal to: σ_ζ, σ_j, σ_φ, σ_{V_o}, σ_{V_g}, σ_{V_c}, σ_k, σ_{z_c}, σ_{z_e}.

3 Empirical Analysis

Data

We solve the model by a first-order approximation around the steady state using Dynare, see Adjemian et al. (2022). The derivation of the steady state is presented in Appendix B. The model is estimated using Bayesian methods on EA data for the following variables: real GDP; real consumption; real investment; employment; GDP deflator growth; HICP of energy products; oil price inflation; coal price inflation; natural gas price inflation; wage inflation; primary energy supply of oil; primary energy supply of coal; primary energy supply of natural gas; the nominal short-term interest rate; and the growth rate of global GDP. Appendix C provides a detailed description of the data sources. The measurement equations are the following:

$$\begin{aligned}
\Delta GDP_t^{data} &= \log(GDP_t) - \log(GDP_{t-1}), & \Delta c_t^{data} &= \log(c_t) - \log(c_{t-1}), \\
\Delta i_t^{data} &= \log(i_t) - \log(i_{t-1}), & \Delta l_t^{data} &= \log(l_t) - \log(l_{t-1}), \\
\pi_t^{data} &= \gamma_\pi + \log(\pi_t), & \pi_{e,t}^{data} &= \gamma_{\pi_e} + \log(\pi_{e,t}), \\
\pi_t^{o,data} &= \gamma_{\pi_o} + \log(\pi_t^o), & \pi_t^{c,data} &= \gamma_{\pi_c} + \log(\pi_t^c), \qquad (19) \\
\pi_t^{g,data} &= \gamma_{\pi_g} + \log(\pi_t^g), & \omega_t^{data} &= \gamma_\omega + \omega_t, \\
V_{o,t}^{data} &= \gamma_{V_o} \times V_{o,t}, & V_{c,t}^{data} &= \gamma_{V_c} \times V_{c,t}, \\
V_{g,t}^{data} &= \gamma_{V_g} \times V_{g,t}, & R_t^{data} &= 400 \times (R_t - 1), \\
\Delta GDP_t^{W,data} &= \log(GDP_t^W) - \log(GDP_{t-1}^W).
\end{aligned}$$

In eq. (19), the constants γ_π, γ_{π_e}, γ_{π_o}, γ_{π_c}, γ_{π_g}, γ_ω, γ_{V_o} , γ_{V_c} and γ_{V_g} ensure that the mean of the model variables is the same as the one of the data variables.[16].

Calibrated Parameters

Following standard practices in the literature on DSGE models (see, among others, Smets and Wouters, 2007, Ireland, 2004, Christiano et al., 2005, and Herbst and Schorfheide, 2015), we fix a subset of the parameters based on economic theory. In addition, we also target the parameters that determine the steady state of the model to match the characteristics of the energy market in the EA.[17] In Table 1 we report the calibrated parameters with their values. First, in steady state the ratio of hours worked in the two sectors is consistent with historical averages. Specifically, after normalizing the hours worked in the core sector to one ($n_c = n_c^{ss} = 1$), the hours worked in the energy sector are equal to $n_e = n_e^{ss} = 0.0116$, this corresponds to 1.1% of the total number of hours

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[16] Note that the data variables ΔGDP_t^{data}, Δc_t^{data} and Δi_t^{data} have been demeaned (see Appendix C), so that they are zero mean variables as their model counterparts and do not have constants in eq. (19)

[17] EA countries are heterogeneous with respect to the economic structure and the mix of energy. Since we are interested in aggregate variables (e.g., prices) that also reflect changes in the energy sector and are influenced by ECB monetary policy, we take the aggregate EA economy into consideration.

worked in the energy sector (see Donoval et al., 2010 and the EU KLEMS database[18]). For the inverse Frisch elasticities of the labor supply (ν_c and ν_e) following Christiano et al. (2005) we select the value of 1. The discount rate is set at $\beta = 0.991$ to give an annual interest rate of 3.60% in steady state. The quarterly capital depreciation rates are equal to $\delta_{k_c} = \delta_{k_e} = 0.025$, which implies annual depreciation rates of 10%. The elasticity of substitution parameters for consumption goods, energy goods and labor varieties (ϵ_{π_c}, ϵ_{π_e}, and ϵ_w) are set to 7.68 to induce steady-state markups of 15%, see Iacoviello and Neri (2010). The capital share parameter for the core sector (α_c) is set to the standard value of 0.30 (Smets and Wouters, 2003), while the capital share parameter for the energy sector (α_e) is set to the value of 0.55 that corresponds to a labor share ($\frac{w_e n_e}{Y_e} X_e = 1 - \alpha_e$) of 0.45 in the energy sector, see Jacquinot et al. (2009).

Regarding the energy related parameters, we normalize the relative price of oil to one, $p_o = p_o^{ss} = 1$. To determine the steady state of the gas price (p_g), in the estimation sample[19] we calculate the average ratios between the price of natural gas per Ton of Oil Equivalent (TOE) and the price of oil per TOE, and set the relative price of gas to the resulting value $p_g = p_g^{ss} = 0.66$. Similarly, taking the average ratios between the price of coal per TOE and the price of oil per TOE, we calibrate the relative price of coal at $p_c = p_c^{ss} = 0.30$, see Appendix C.

Following Jacquinot et al. (2009), for households we target a steady state share of energy expenditure on total expenditure equal to 6%, which implies $\omega_{c_c} = 0.94$. Since the average of intermediate energy inputs on production is 3% in EA (see Donoval et al., 2010 and the EU KLEMS database) and the ratio of production over capital is 17% (see EU KLEMS database), we fix the steady-state share of intermediate energy over capital $s_{m_e,k_c} \equiv \frac{m_e}{k_c} = 0.03 \times 0.17 = 0.0052$. Following Jacquinot et al. (2009), we target a cost share of crude energy over energy production costs to 33.5% in steady state, $s_{p_v V_e, Y_e} \equiv \frac{p_v V_e}{Y_e} = 0.335$. By computing the ratio between the available quantity of natural gas and oil in the EA in the estimation sample (both expressed in TOE), we obtain a target ratio of gas to oil of 51%, $s_{V_g,V_o} \equiv \frac{V_g}{V_o} = 0.51$.

Following the same procedure for the ratio of coal to oil (s_{V_c,V_o}), we impose $s_{V_c,V_o} \equiv \frac{V_c}{V_o} = 0.33$. In Appendix B, we describe in detail how the calibration targets are linked to

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[18] *Source:* EU KLEMS data: `www.euklems.net`.

[19] We do not consider the last ten quarters to avoid biases due to large shocks.

the steady state of the model variables.

Table 1: Calibrated parameters. The table reports the parameter's name (Full Name), the associate symbol (Symbol), and the calibrated value (Value).

Economic parameters		
Full Name	Symbol	Value
Hours worked in $\mathcal{S}_c$	n_c^{ss}	1.000
Hours worked in $\mathcal{S}_e$	$100 \times n_e^{ss}$	1.160
Depreciation $\mathcal{S}_c$	δ_{k_c}	0.025
Inverse Frisch elast. $\mathcal{S}_c$	ν_c	1.000
Inverse Frisch elast. $\mathcal{S}_e$	ν_e	1.000
Capital share $\mathcal{S}_c$	α_c	0.350
Depreciation $\mathcal{S}_e$	δ_{k_e}	0.025
Capital share $\mathcal{S}_e$	α_e	0.550
Discount factor	β	0.991
Elast. substitution of goods $\mathcal{S}_c$	ϵ_{π_c}	7.677
Elast. substitution of goods $\mathcal{S}_e$	ϵ_{π_e}	7.677
Elast. substitution of labor varieties	ϵ_w	7.677

Energy parameters		
Full Name	Symbol	Value
Relative price of oil	p_o^{ss}	1.000
Relative price of natural gas	p_g^{ss}	0.660
Relative price of coal	p_c^{ss}	0.300
Share of non-energy expenditure in consumption	ω_{c_c}	0.940
Share of refined energy in S_c production	s_{m_e,k_c}	0.005
Share of raw energy in $\mathcal{S}_e$ production	$s_{p_v V_e,Y_e}$	0.335
Ratio of gas to oil	s_{V_g,V_o}	0.510
Ratio of coal to oil	s_{V_c,V_o}	0.330
Steady-state common factor	p_f^{ss}	0.826

Estimation

We estimate the model parameters on quarterly data of the EA from 1990:Q1 to 2020:Q1 and then use these parameters to smooth out the shocks realized between 2020:Q2 and 2022:Q4, similarly to Boragan Aruoba et al., 2018, Brinca et al., 2020 and Faria-e Castro, 2021. We use a standard Random Walk Metropolis-Hastings (RWMH) algorithm to target the posterior distribution of the model parameters. The prior selection is in line with the existing literature on medium-scale DSGE models (Smets and Wouters, 2003) and is reported in Tables 2 and 3. The parameters that determine the rigidity of prices and wages appearing in the adjustment costs *à la* Rotemberg (η_{π_e}, η_{π_c} and η_w), are unbounded and lack economic interpretability. We then link these parameters to the fractions of firms and unions that cannot reset prices and wages in an equivalent setting *à la* Calvo, see

Richter and Throckmorton (2016). These fractions are, respectively, denoted by θ_{π_e}, θ_{π_c} and θ_w (the complete optimization problems of retailers and labor unions are presented in Appendix A), and their dependence on η_{π_e}, η_{π_c} and η_w is:

$$\eta_i = \frac{\theta_i(\epsilon_i - 1)}{(\beta\theta_i - 1)(\theta_i - 1)}, \qquad i = \pi_e, \pi_c, w.$$

For θ_{π_e} and θ_{π_c} we select Beta ($\mathcal{B}$) priors with means equal to 0.75 and standard deviations equal to 0.05 as in Smets and Wouters (2003), suggesting an average price duration of one year. For the wage rigidity parameter (θ_w) we select a $\mathcal{B}$ prior with a mean equal to 0.50, suggesting a medium degree of wages rigidity. For the habit parameter in consumption (h), we set a $\mathcal{B}$ prior with a mean equal to 0.50, as in Iacoviello and Neri (2010). In addition, the priors for the parameters θ_l, r_R, r_Y, r_π, ι_{π_c}, ι_{π_e} follow directly Smets and Wouters (2003). The specification of investment adjustment costs follows Iacoviello and Neri (2010), so for η_k, the parameter determining the rigidity of capital (see Appendix A), we use the prior of these authors. For the parameter that determines the rigidity of capacity utilization, η_u, we use a $\mathcal{B}$ prior centered on the mean value of 0.50, as in Smets and Wouters (2007) and Iacoviello and Neri (2010). The prior for the indexation parameter of wages (ι_w) is the same as for prices, see Smets and Wouters (2003). For the substitution elasticity (σ_v) between oil, coal, and gas in the crude energy aggregator, we select a rather loose prior around the benchmark value as in Golosov et al. (2014), namely 0.95. For the substitution elasticity between the energy sector and the consumption goods of the core sector (σ_c) and for the substitution elasticity between the intermediate energy and the raw capital of the core sector (σ_{k_c}), we select a Gamma prior ($\mathcal{G}$) around the value of 0.54, as in Acurio Vásconez (2015). The parameters in the second part of Table 2 are the constants appearing in the measurement equations (19), and for them we use Normal ($\mathcal{N}$) priors with a mean equal to the average of the corresponding observed series and with a standard deviation equal to ten percent of this average. The prior distributions of the parameters of the shock processes, Table 3, are $\mathcal{B}$ for the persistence parameters and Inverse Gamma ($\mathcal{IG}$) for the standard deviations of the shocks. The parameters of the SVAR appearing in the matrices in eq. (7) are estimated together with the other model parameters, and their prior density is $\mathcal{N}$ and is based on a preliminary estimation on a presample. The prior and posterior of the SVAR parameters are reported in the Appendix D.

Table 2: Estimation results. The table shows the endogenous propagation parameters and the measurement equations parameters. The table reports the parameter's name (Full Name) with the associate symbol (Symbol). The table also reports the prior shape (Prior), prior mean and standard deviation (Mean, St. Dev), and the posterior mean (Post. Mean) and standard deviation (Post. St. Dev) for the estimated parameters. The $\mathcal{B}$ is the Beta distribution; $\mathcal{N}$ is the Normal distribution; $\mathcal{G}$ is the Gamma distribution; $\mathcal{IG}$ is the Inverse-Gamma distribution.

Endogenous propagation parameters

Full Name	Symbol	Prior	Mean, St. Dev.	Post. Mean	Post. St. Dev
Habits	h	$\mathcal{B}$	(0.70, 0.10)	0.99	0.00
Price Rigidity $\mathcal{S}_c$	θ_{π_c}	$\mathcal{B}$	(0.75, 0.05)	0.79	0.03
Price Rigidity $\mathcal{S}_e$	θ_{π_e}	$\mathcal{B}$	(0.75, 0.05)	0.78	0.01
Employment Rigidity	θ_l	$\mathcal{B}$	(0.50, 0.15)	0.89	0.01
Taylor Rule Inertia	r_R	$\mathcal{B}$	(0.80, 0.10)	0.88	0.01
Taylor Rule Output	r_Y	$\mathcal{N}$	(0.13, 0.05)	0.23	0.05
Taylor Rule Inflation	r_π	$\mathcal{N}$	(1.70, 0.10)	1.52	0.08
Price Indexation $\mathcal{S}_c$	ι_{π_c}	$\mathcal{B}$	(0.75, 0.15)	0.18	0.06
Price Indexation $\mathcal{S}_e$	ι_{π_e}	$\mathcal{B}$	(0.75, 0.15)	0.03	0.01
Wage Rigidity	θ_w	$\mathcal{B}$	(0.50, 0.05)	0.88	0.01
Wage Indexation	ι_w	$\mathcal{B}$	(0.75, 0.15)	0.96	0.03
Cap. Adj. Cost	η_k	$\mathcal{G}$	(10.00, 2.50)	26.60	2.74
Utiliz. Adj. Cost	η_u	$\mathcal{B}$	(0.50, 0.05)	0.53	0.04
El. Subst. Crude Energy	σ_v	$\mathcal{G}$	(0.95, 0.20)	0.67	0.04
El. Subst. Energy Consumption	σ_c	$\mathcal{G}$	(0.54, 0.20)	0.50	0.08
El. Subst. Energy Production	σ_{k_c}	$\mathcal{G}$	(0.54, 0.20)	0.33	0.12

Measurement equations parameters

Full Name	Symbol	Prior	Mean, St. Dev.	Post. Mean	Post. St. Dev
Meas. Const. Inflation	$100 \times \gamma_\pi$	$\mathcal{N}$	(0.49, 0.05)	0.43	0.04
Meas. Const. Inflation $\mathcal{S}_e$	$100 \times \gamma_{\pi_e}$	$\mathcal{N}$	(0.73, 0.07)	0.61	0.06
Meas. Const. Oil Price	$100 \times \gamma_{\pi_o}$	$\mathcal{N}$	(0.69, 0.07)	0.78	0.06
Meas. Const. Gas Price	$100 \times \gamma_{\pi_g}$	$\mathcal{N}$	(0.57, 0.06)	0.66	0.06
Meas. const. Coal Price	$100 \times \gamma_{\pi_c}$	$\mathcal{N}$	(0.60, 0.06)	0.58	0.06
Meas. Const. Wage Inflation	$100 \times \gamma_\omega$	$\mathcal{N}$	(0.66, 0.07)	0.88	0.04

The posterior mean and standard deviation of the estimated parameters are shown in Tables 2 and 3. The posterior estimates point to a high degree of consumption habits (h). The rigidities of prices (θ_{π_c} and θ_{π_e}) are similar in the two sectors and suggest an average duration of prices of around five quarters. The indexation of prices is modest in the core sector (ι_{π_c}) and is almost absent in the energy sector (ι_{π_e}). The high degree of employment rigidity (θ_l) suggests that employment responds sluggishly to hours worked. Estimates for the Taylor rule suggest a substantial degree of smoothing of the interest rate (r_R), and a moderate response of the interest rate to GDP (r_Y) and inflation (r_π). Estimates related to wage dynamics suggest a high degree of wage stickiness (θ_w) and a high degree of wage

Table 3: Estimation results. The table shows the exogenous processes parameters. The table reports the parameter's name (Full Name) with the associate symbol (Symbol). The table also reports the prior shape (Prior), prior mean and standard deviation (Mean, St. Dev), and the posterior mean (Post. Mean) and standard deviation (Post. St. Dev) for the estimated parameters. The $\mathcal{B}$ is the Beta distribution; $\mathcal{IG}$ is the Inverse-Gamma distribution.

Exogenous processes parameters

Full Name	Symbol	Prior	Mean, St. Dev.	Post. Mean	Post. St. Dev
Persistence Prod. $\mathcal{S}_c$	ρ_{z_c}	$\mathcal{B}$	(0.50, 0.10)	0.98	0.01
Persistence Prod. $\mathcal{S}_e$	ρ_{z_e}	$\mathcal{B}$	(0.50, 0.10)	0.41	0.06
Preference for $\mathcal{S}_e$	ρ_j	$\mathcal{B}$	(0.50, 0.10)	0.96	0.01
Persistence Lab. Supply	ρ_φ	$\mathcal{B}$	(0.50, 0.10)	0.97	0.01
Persistence Intertemp.	ρ_ζ	$\mathcal{B}$	(0.50, 0.10)	0.64	0.04
Persistence Prod. Inv.	ρ_k	$\mathcal{B}$	(0.50, 0.10)	0.93	0.02
Persistence Oil Price	ρ_{p_o}	$\mathcal{B}$	(0.50, 0.10)	0.98	0.01
Persistence Gas Price	ρ_{p_g}	$\mathcal{B}$	(0.50, 0.10)	0.75	0.07
Persistence Coal Price	ρ_{p_c}	$\mathcal{B}$	(0.50, 0.10)	0.90	0.03
Persistence Oil Prod.	ρ_{V_o}	$\mathcal{B}$	(0.50, 0.10)	0.59	0.05
Persistence Gas Prod.	ρ_{V_g}	$\mathcal{B}$	(0.50, 0.10)	0.59	0.07
Persistence Coal Prod.	ρ_{V_c}	$\mathcal{B}$	(0.50, 0.10)	0.81	0.07
St. Dev. Prod. $\mathcal{S}_c$	$100 \times \sigma_{z_c}$	$\mathcal{IG}$	(0.10, 1.00)	1.06	0.13
St. Dev. Temp. Mon. Policy	$100 \times \sigma_e$	$\mathcal{IG}$	(0.10, 1.00)	10.89	0.82
St. Dev. Prod. $\mathcal{S}_e$	$100 \times \sigma_{z_e}$	$\mathcal{IG}$	(0.10, 1.00)	11.52	1.47
St. Dev. Intratemp.	$100 \times \sigma_j$	$\mathcal{IG}$	(0.10, 1.00)	4.33	0.72
St. Dev. Pers. Mon. Policy	$100 \times \sigma_r$	$\mathcal{IG}$	(0.10, 1.00)	0.17	0.14
St. Dev. Lab. Supply	$100 \times \sigma_\varphi$	$\mathcal{IG}$	(0.10, 1.00)	11.76	1.55
St. Dev. Pref.	$100 \times \sigma_\zeta$	$\mathcal{IG}$	(0.10, 1.00)	24.84	5.70
St. Dev. Oil Price	$100 \times \sigma_{p_o}$	$\mathcal{IG}$	(0.10, 1.00)	7.45	1.06
St. Dev. Gas Price	$100 \times \sigma_{p_g}$	$\mathcal{IG}$	(0.10, 1.00)	10.39	0.82
St. Dev. Coal Price	$100 \times \sigma_{p_c}$	$\mathcal{IG}$	(0.10, 1.00)	4.06	0.29
St. Dev. Oil Prod.	$100 \times \sigma_{V_o}$	$\mathcal{IG}$	(0.10, 1.00)	11.90	2.42
St. Dev. Gas Prod.	$100 \times \sigma_{V_g}$	$\mathcal{IG}$	(0.10, 1.00)	28.05	4.87
St. Dev. Coal Prod.	$100 \times \sigma_{V_c}$	$\mathcal{IG}$	(0.10, 1.00)	22.74	5.33
St. Dev. Prod. Inv.	$100 \times \sigma_k$	$\mathcal{IG}$	(0.10, 1.00)	1.79	0.19
St. Dev. Common Factor	$100 \times \sigma_{p_f}$	$\mathcal{IG}$	(0.10, 1.00)	13.18	1.02
St. Dev. Global GDP	$100 \times \sigma_W$	$\mathcal{IG}$	(0.10, 1.00)	0.37	0.03

indexation to prices (ι_w). We estimate a high degree of investment adjustment cost (η_k) and a medium rigidity of capacity utilization (η_u). The substitution elasticity between oil, coal and gas (σ_v), the substitution elasticity of energy in consumption (σ_c) and the substitution elasticity of energy in production (σ_{k_c}) are estimated to be below one, pointing to a low substitutability of energy. The role of the estimated parameters on the model dynamics is further discussed in the next section.

4 Economic Results

IRFs

In Figure 5 we report the Impulse Response Functions (IRFs) associated with an unexpected rise in the price of natural gas (p_g), caused by a shock (ε_{p_g}) to the idiosyncratic component of gas price a_{p_g}, see eq. (6). The shock reduces the amount of natural gas (V_g) used by firms in the energy sector for the production of refined energy. This leads to an increase in the price index of crude energy (p_v), and in the price of refined energy (p_e) charged by energy firms. Higher energy prices reduce the demand for energy by firms in the core sector (m_e) and households energy consumption (c_e). GDP decreases due to the lower level of intermediate energy in the production of firms in the core sector and the lower energy demand from households. Finally, higher energy prices lead to an increase in general inflation (π), so this shock has the characteristics of a negative supply shock. In Appendix E we show a similar dynamics of the IRFs to idiosyncratic shocks to the price of oil, coal and to the common factor of crude energy prices.[20]

Pandemic shocks

Our estimated model provides a historical decomposition of the shocks generated by the pandemic in 2020 and the subsequent energy price shocks from 2021 onwards. Figure 6 shows the smoothed shocks realized in the sample, zoomed between 2015:Q1 and 2022:Q4.[21] The main shocks that drive the COVID-19 pandemic recession and the recovery are visible in the last part of the sample. First, the pandemic resulted in a large increase in labor disutility (ε_{φ}), determining the large contraction in hours worked in 2020:Q2. This shock shows an opposite movement in 2020:Q3, due to reopening and the rebound in hours worked. The discount factor shock (ε_{ζ}) shows substantial movements in 2020:Q2 and 2020:Q3. First, it is negative (increasing savings and decreasing consumption) due to the decline in the demand for goods during the lockdown and then positive (decreasing savings and increasing consumption) after the partial easing of the social distancing measures. The productivity of the energy sector (ε_{z_e}) is positive in 2020:Q2 and negative in

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[20] We focus on gas price shocks in the main text due to the large hikes of gas price in our sample and relegate economic simulations regarding oil, coal and the common factor of crude energy prices in Appendix E.

[21] The smoothed shocks are obtained by running the Kalman smoother using the parameter at the posterior mean in Tables 2 and 3 on the full sample (from 1990:Q1 to 2022:Q4).

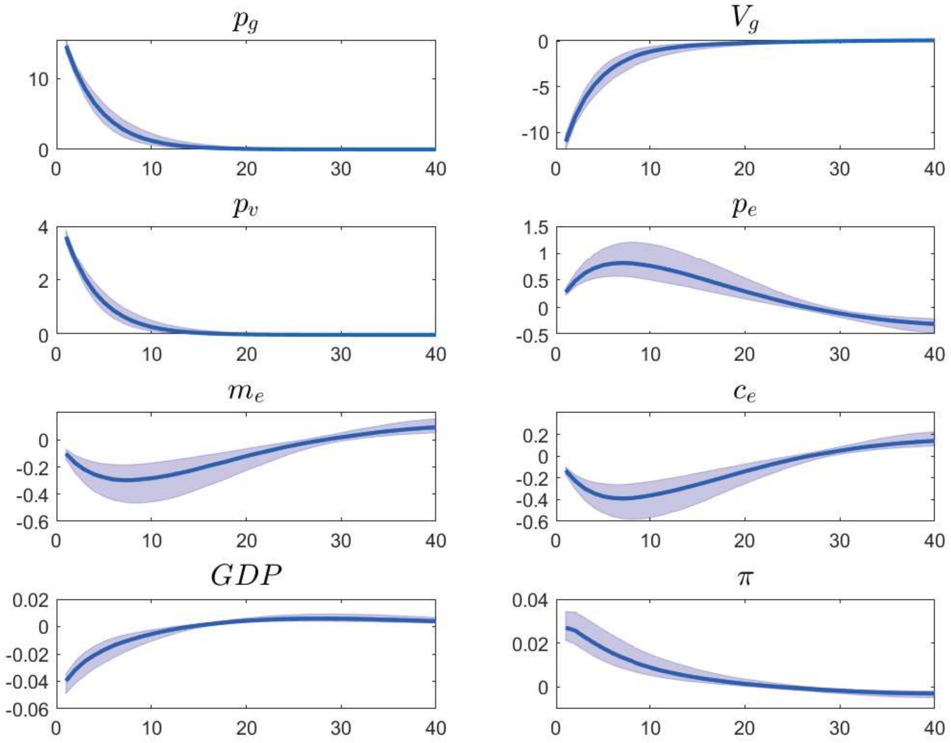


Figure 5: The IRFs of key model variables to a natural gas price shock. The shaded areas represent credible bands related to parameter uncertainty between the 20th and 80th percentiles. The IRFs represent percentage deviations from the steady state.

2020:Q3, as energy prices fell during the outbreak of the pandemic and increased during recovery. The decline in global energy demand during the pandemic results in negative movements in oil, coal, and gas prices (ε_{p_o}, ε_{p_c} and ε_{p_g}), and positive movements in the aftermath of the pandemic (first due to recovery in global demand, then due to growing geopolitical tensions).

On the households' side, the demand shock on the energy consumption good (ε_j) first shows a negative movement in 2020:Q2, and then a rebound, representing the recovery in energy demand, leading to higher energy prices. The investment productivity shock (ε_k) shows a large negative movement in 2020:Q3, reflecting a contraction in capital goods investment during the recovery from the pandemic. The shock to global GDP (ε_W) shows first a negative movement in 2020:Q2, and then a rebound in 2020:Q3, due to the rapid recession and recovery that unfolded worldwide. Finally, after 2020:Q3, the shock to the common factor of crude energy prices (ε_{p_f}) shows a sequence of positive movements, resulting in a general increase in commodity prices during the recovery.

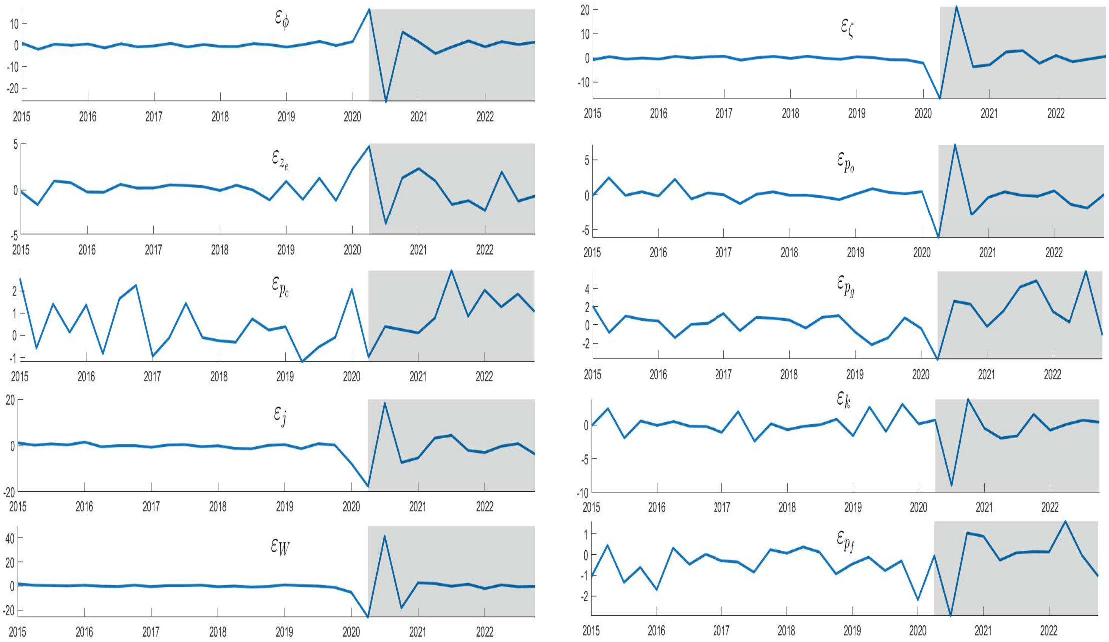


Figure 6: The smoothed shocks realized in the sample. The shocks have been standardized by dividing the smoothed shocks by their respective standard deviations and have been calculated using the posterior mean of the model parameters presented in Tables 2 and 3. The gray-shaded area represents the quarters after the outbreak of the pandemic, namely 2020:Q2 and afterward. ε_{φ} *is the labor supply shock;* ε_{ζ} *is the discount factor shock;* ε_{z_e} *is the productivity shock to* $\mathcal{S}_e$*;* ε_{p_o} *is the oil price shock;* ε_{p_c} *is the coal price shock;* ε_{p_g} *is the gas price shock;* ε_{j} *is the energy demand shock;* ε_{k} *is the investment productivity shock;* ε_{W} *is the shock to global GDP;* ε_{p_f} *is the shock to the common factor of crude energy prices.*

Figure 7, provides a counterfactual analysis to assess the economic impact of the shocks described previously. We evaluate the impact of the pandemic and energy shocks by shutting down all innovations realized from 2020:Q2 onward. The figure compares the actual observations (smoothed, solid blue lines) of the indicated variables to the counterfactuals (No Pandemic, dashed red lines). The upper left panel of Figure 7 shows the dynamics of the general inflation rate (π), which initially decreases during the first wave of the pandemic and then shows consecutive positive values from 2020:Q4 as a result of both recovery and energy shocks; in their absence (red dashed line), the inflation rate would have moved far less. The upper right panel of Figure 7 reports the HICP inflation of energy products (π_e). We find that the movements in this series in 2020-2022 were mostly unanticipated and that the counterfactual path, without the pandemic and energy shocks, does not show the large deflation during the pandemic and the upswing after 2021. More specifically, this is due to (i) shocks that have negative impact on energy prices (positive shocks to energy sector productivity, ε_{z_e}; negative shocks on the prices of crude energy, ε_{p_o}, ε_{p_c}, ε_{p_g}; negative energy demand shocks, ε_{j}; and indirect effects of the decreased energy demand of

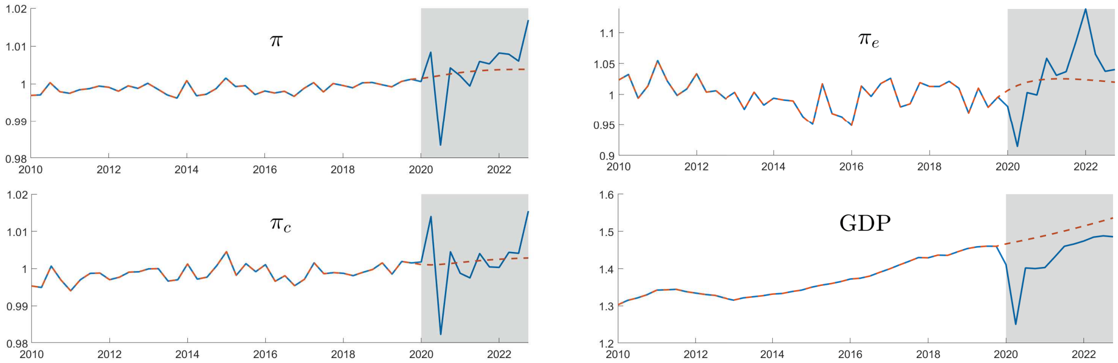


Figure 7: The counterfactual variables obtained by switching off all the 2020-2022 shocks. The plots represent general inflation (π), energy products inflation (π_e), core inflation (π_c) and the level of the real gross domestic product (GDP). Solid blue lines represent the actual realizations computed with all the smoothed shocks switched on, while dashed red lines represent the counterfactual series obtained by muting all the shocks realized in 2020:Q2 and afterward. The gray-shaded area represents the quarters after the outbreak of the pandemic, namely 2020:Q2 and afterward.

households and core firms coming from other recession shocks) and (ii) rebound shocks in the opposite direction (negative shocks to energy sector productivity, ε_{z_e}; positive shocks on the price of crude energy ε_{p_o}, ε_{p_c}, ε_{p_g}; positive energy demand shocks, ε_j; and indirect effects from increased energy demand by households and core firms coming from other rebound shocks).

The lower left panel of Figure 7 shows the counterfactual regarding core inflation (π_c). This allows us to disentangle the effects of the 2020-2022 shocks on inflation (π), excluding the direct pass-through effects from movements in the inflation of energy products (π_e). The series (π_c) closely resembles π, as energy inflation has a small weight in general inflation (see eq. 16). Finally, the lower right panel shows the counterfactual of the level of GDP; in the absence of the pandemic and energy shocks of 2020-2022, GDP movements are far smaller and at the end of the sample GDP is still below the pre-pandemic trend.

Energy shocks

To separate the effect of energy shocks from other shocks, in a second counterfactual exercise we mute all the shocks to oil, coal, gas prices and the common factor (ε_{p_o}, ε_{p_c}, ε_{p_g}, ε_{p_f}) that occur from 2021:Q1 to the end of the sample, see Figure 8. The upper left panel, reports the effect of energy shocks on general inflation (π). Between 2021:Q1 and 2022:Q4, energy shocks put positive pressure on general inflation in the EA. Without energy shocks, given the change in inflation reported in Figure 8, the general price level P would have increased by approximately 5.96%, instead of 8.60%. The effect is also evident

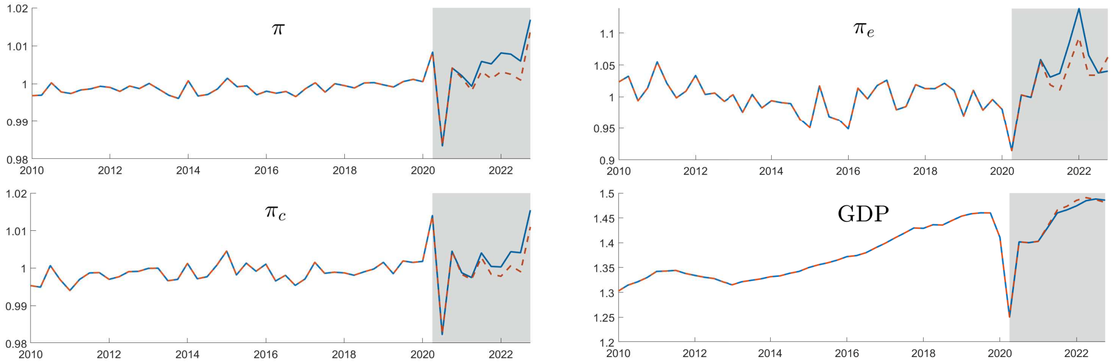


Figure 8: The counterfactual variables obtained by switching off the shocks to the price of crude energy. The graphs represent general inflation (π), inflation of energy products (π_e), core inflation (π_c) and the growth rate of the real gross domestic product (GDP). The solid blue lines represent the actual realizations computed with all the smoothed shocks switched on, while the dashed red lines represent the counterfactual series obtained by muting all the shocks realized in 2020:Q2 and afterward. The gray-shaded area represents the quarters after the outbreak of the pandemic, namely 2020:Q2 and afterward.

for the inflation on the energy products π_e (upper right panel), in this case the increase in the energy price level (P_e) is 54% of which 13% is due to energy shocks. The third panel of Figure 8 shows the impact of energy shocks on core inflation. This impact depends on two channels. First, there is a direct pass-through of energy shocks to the prices of the core sector due to the presence of intermediate energy inputs (m_e) in the production of the core sector (*production channel*). Second, energy shocks affect the price level of the core sector due to changes in the demand for core goods that follow substitution effects in the consumption basket after the increase in the energy price (*consumption channel*). Overall, oil, coal, and gas price shocks contribute to upward pressure on the core price, without these shocks, core inflation would have increased less in the 2021-2022 period. Finally, the lower right panel shows the counterfactual for the level of GDP. Between 2021:Q1 and 2022:Q2 energy shocks negatively influenced GDP; however, in the last two quarters of 2022 these shocks positively affected GDP due to a decline in crude energy prices. Figure 9 shows the cumulative GDP losses as a percentage of the GDP level in 2020:Q4; cumulative GDP losses reach the highest value of 2% at 2022:Q2 then decrease slightly. This is in line with Liadze et al. (2022), who attributed an effect of the Russian-Ukrainian War to the GDP of Europe between -1% and -2%.

Figure 10 shows the contribution shares of energy sources to the increase in the general price level (P) from 2021:Q1 to 2022:Q4. The shares are obtained by considering counterfactual for the prices of oil, coal and gas (p_o, p_c and p_g) that keep these prices at the 2021:Q1 level. To compute them we simulate paths of idiosyncratic shocks to oil, coal

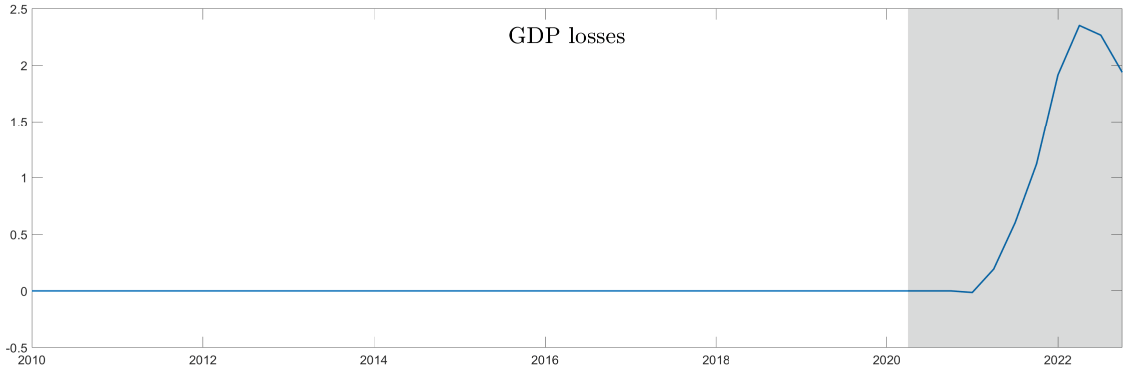
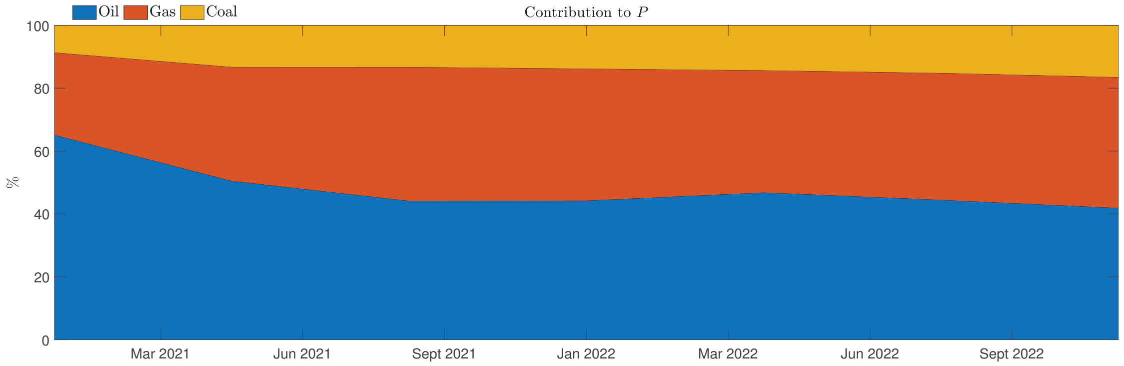


Figure 9: GDP losses due to energy shocks. GDP losses have been calculated as the sum of the differences of GDP between the 2021:Q1 and 2022:Q4 in the case energy shocks do not (do) realize, as a percentage the level of GDP in 2020:Q4.

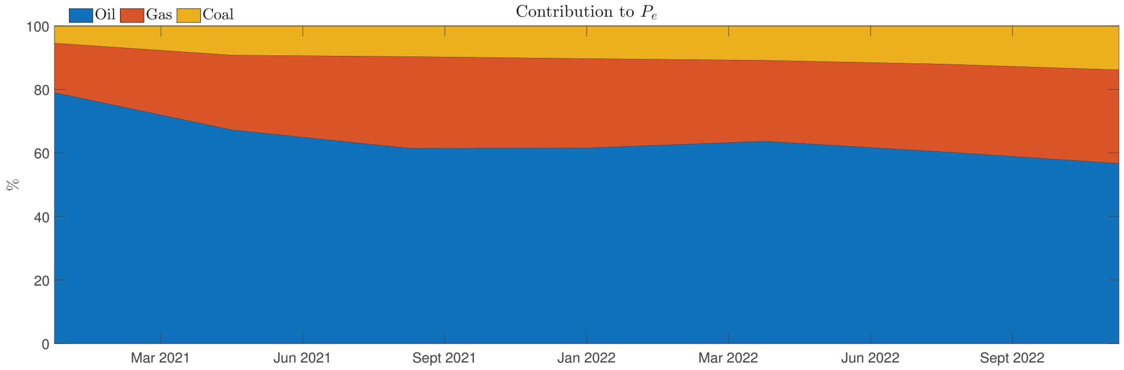
and gas (ε_{p_o}, ε_{p_v} and ε_{p_g}) that offset the increase in the price of the common factor p_f (see eq. 5). At the end of the sample, the contribution of oil to the movement of prices is 41.9%, the contribution of gas is 41.6% and the contribution of coal is the remaining 16.5%. Oil plays an important role because its steady-state price per unit of energy is higher than the price of gas and coal (as shown by the values of the relative prices of oil, gas and coal, p_o^{ss}, p_g^{ss} and p_c^{ss}, in Table 1), and also because it is the most used energy input in production (as shown by the values of the ratio of gas to oil, s_{V_g,V_o}, and coal to oil, s_{V_c,V_o}, in Table 1). Natural gas, despite having a smaller share than oil in the economy, has a comparable contribution in explaining the movements of the general price level, as its price is the one that recorded the highest increase. The bottom panel of Figure 10 shows that similar contribution shares are found for the energy price level (P_e), but in this case oil is even more important.

The role of complementarities

The parameters σ_{k_c} and σ_c determine the elasticity of substitution between energy and non-energy goods in production and consumption, and are estimated to be significantly below one. This implies a low substitutability of energy in production and consumption, as shown in Table 2. We compute the IRFs while adjusting these two parameters in order to demonstrate how these complementarities impact the economic transmission of energy shocks. The upper panel of Figure 11 reports the IRF of GDP to a positive shock (ε_{p_g}) to the price of natural gas (p_g) for different values of σ_{k_c}. When the elasticity σ_{k_c} decreases (i.e. the production process becomes less flexible), the negative effect on GDP



(a) Contribution to the general price level (P).



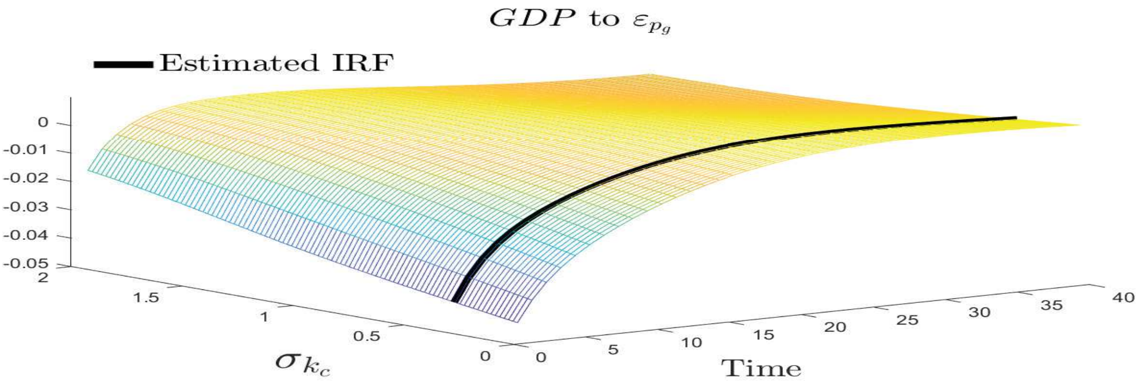
(b) Contribution to the energy price level (P_e).

Figure 10: Contribution shares of oil, gas and coal. The plots show the relative importance in percentage of oil (blue), gas (orange) and coal (yellow) to the movements in the general price level (P, top panel) and in the energy price level (P_e, bottom panel) from 2021:Q1 to 2022:Q4. On the vertical axis, 100% represents the total contribution of oil, gas and coal to the movement of prices between 2021:Q1 and the indicated quarter on the horizontal axis.

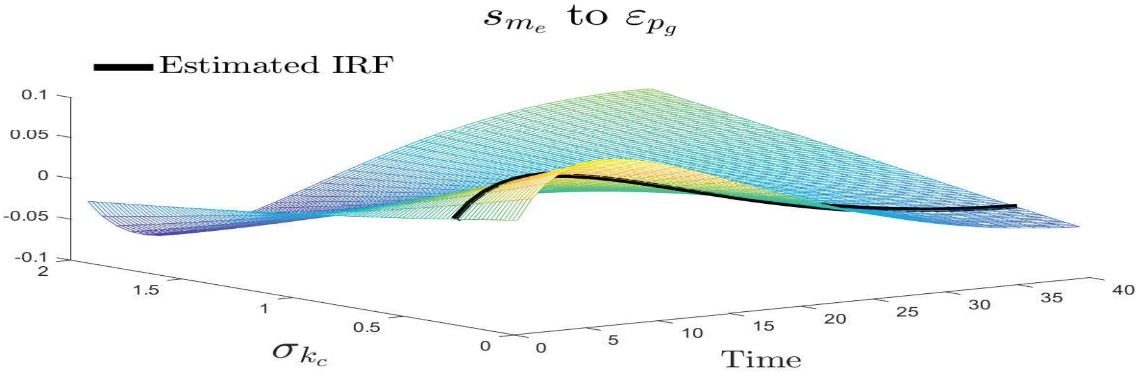
is amplified. The effects of a gas price shock on GDP are 27% greater on impact with our estimated σ_{k_c} (black solid line) than for the case of unitary substitution elasticity ($\sigma_{k_c} = 1.00$). The lower panel of Figure 11, shows the response of the share of energy costs on the total costs of intermediate energy (m_e) and capital (k_e) paid by the firms in the core sector ($s_{m_e} \equiv \frac{p_e m_e}{r_{k_e} u_{k_e} k_e + p_e m_e}$). In the case of our estimated σ_{k_c} which is below one (complementarity), when the price of natural gas increases, the share of energy costs over total capital costs increases. The share is constant in the case of a unitary σ_{k_c} (Cobb-Douglas case), while in the case of σ_{k_c} greater than one (substitutes), the share decreases. In Appendix E we also show similar results related to shocks to oil and coal prices.

In Figure 12, we perform a comparable analysis by varying the elasticity of substitution between energy and non-energy goods in consumption (σ_c). Here, a gas price shock leads to a rise in the prices of refined energy goods (c_e), and affects the consumption of goods from the core sector (c_c). The solid black line represents the IRF when the elasticity of substitution equals our estimate (0.50). Compared to the case where the elasticity is higher, our estimated σ_c implies that the composition of households' consumption changes less, with a milder effect on GDP.

Furthermore, as the solid black line in Figure 12 shows, for our estimated σ_c the share of household expenditure on energy products over total consumption ($s_{c_e} \equiv \frac{p_e c_e}{c_c + p_e c_e}$) increases after a gas price shock, since complementarity reduces energy demand less proportionally than the increase in the price of energy after the shock. Additional results related to oil, coal, common factor shocks and wage indexation are reported in the Appendix E.



(a) IRF of GDP

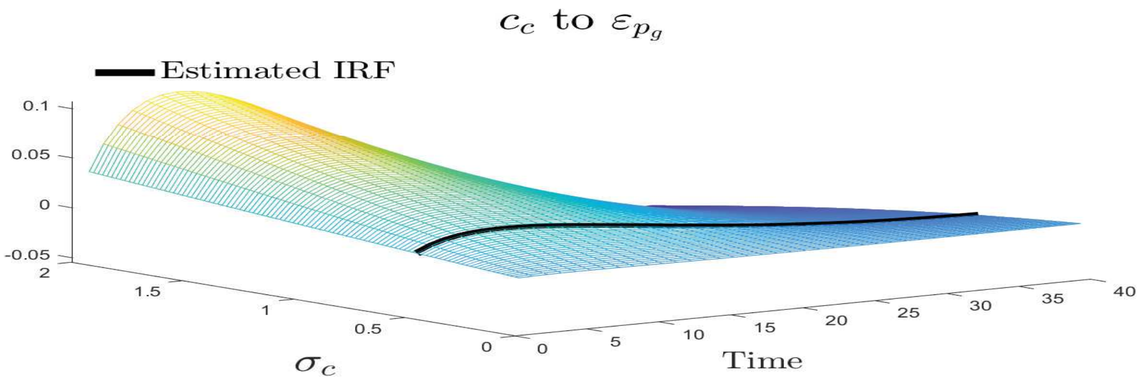


(b) IRF of s_{m_e}

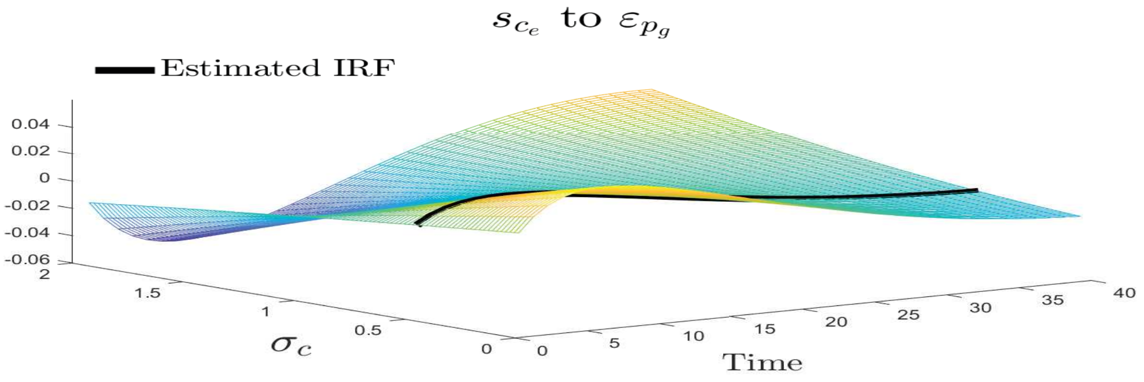
Figure 11: The impact of the elasticity of substitution in production on the transmission of gas price shocks. The plots represent the IRFs to a positive one standard deviation shock (ε_{p_g}) to the price of natural gas (p_g), computed at different values of the elasticity of substitution parameter σ_{k_c}. The black line represents the IRF at the estimated value of σ_{k_c}. The IRFs represent percentage deviations from the steady state.

The role of wage indexation

The wage indexation parameter ι_w influences the response of the economy to an energy price shock. Our estimate (ι_w = 0.96) suggests that wages adjust substantially to price



(a) IRF of c_e



(b) IRF of s_{c_e}

Figure 12: The impact of the elasticity of substitution in consumption on the transmission of gas price shocks. The plots represent the IRFs to a positive one standard deviation shock (ε_{p_g}) to the price of natural gas (p_g), computed at different values of the elasticity of substitution parameter σ_c. The black line represents the IRF at the estimated value of σ_c. The IRFs represent percentage deviations from the steady state.

movements. Figure 13 shows the response of GDP to a positive shock to the price of natural gas (ε_{p_g}), for different values of the wage indexation parameter ι_w. The plot shows that as price indexation increases, the effects of gas price shocks on GDP are larger. By comparing the IRF obtained with our estimated parameter, we observe that after 20 quarters the cumulative effects of this shock on output are about three times larger with respect to medium level indexation ($\iota_w = 0.50$). In the higher indexation scenario, the upward pressure on prices feeds back to higher nominal wages, amplifying the effects of energy shocks on production costs and GDP.[22] In Appendix E, we show similar results of shocks to oil, coal and to the common factor of crude energy prices.

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[22] On the empirical side, Donoval et al. (2010) provide reduced-form evidence that in European countries with higher levels of wage indexation, the effects of oil price shocks are larger.

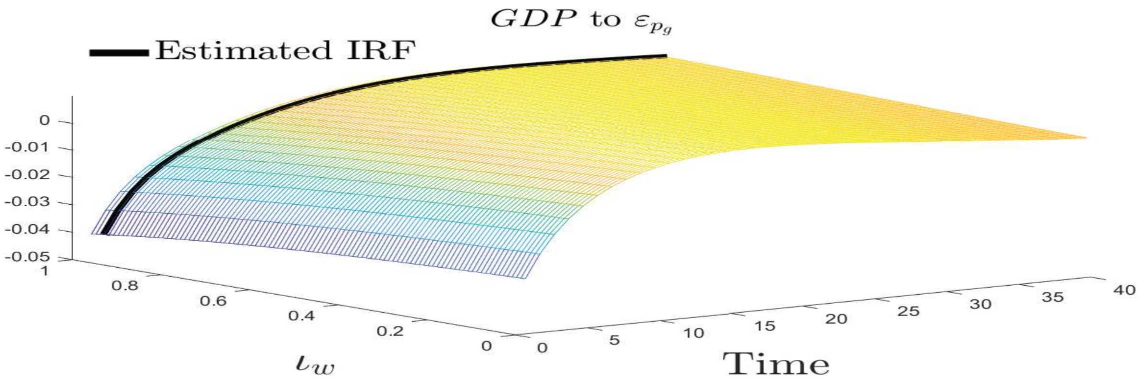


Figure 13: The role of wage indexation on the transmission of gas price shocks. The plots represent the IRFs of GDP to a positive one standard deviation natural gas price shock (ε_{p_g}), depending on the degree of wage indexation (ι_w). The black line represents the IRF at the estimated value of ι_w. The IRFs represent percentage deviations from the steady state.

Keynesian supply shocks

The Keynesian supply shocks (KSS) originate from supply reductions (e.g., supply chain disruptions) that trigger a decrease in aggregate demand that is greater than the original supply reduction, see Guerrieri et al. (2022). This results in a reduction in prices since these shocks are effectively transmitted as demand shocks. Guerrieri et al. (2022) identify various transmission channels that make supply shocks KSSs, including complementarities in consumption, incomplete markets, and firm exit. Given the possible KSS characterization of negative energy supply shocks in our model, we apply the analysis of Guerrieri et al. (2022) originally devised for pandemic shocks. Section 4, shows that the overall effects of energy shocks on core sector prices (P_c) are positive, ruling out the possible characterization of energy shocks as KSS. To distinguish key model features that differentiate our setup from that of Guerrieri et al. (2022), we plot in Figure 14 the IRFs of the core sector inflation rate (π_c) to generic supply shock to the common factor of crude energy prices. Our estimated parameters (Baseline model, blue solid line) produce a positive response of π_c to an energy shock, implying a positive passthrough from energy prices to core sector prices, therefore excluding KSSs. To reconduct our model to key characteristics of the styled model of Guerrieri et al. (2022), we analyze the case where, consistent with their framework, there are no consumption habits ($h \approx 0$), wages are flexible ($\theta_w \approx 0$), and energy is used only for consumption and not in production ($s_{m_e,k_c} \approx 0$). Moreover, we set the elasticity of substitution between energy and core goods in consumption to a low value ($\sigma_c = 0.01$), to make energy goods and core goods strong complements. In this scenario, represented by the dashed red line, the response of core sector inflation is negative, mimicking the effects of a negative demand shock hitting the general sector of the economy. When consumption goods are strong complements and consumption habits are ruled out, a decrease in consumption of energy goods triggers a decrease in demand for core sector goods (*consumption channel*) large enough to decrease their prices. In this case, intermediate energy in production is switched off ($s_{m_e,k_c} \approx 0$), so higher energy prices do not translate into higher marginal costs of the core sector due to the presence of energy in the production function (eq. 9) and higher final goods prices (*production channel*).

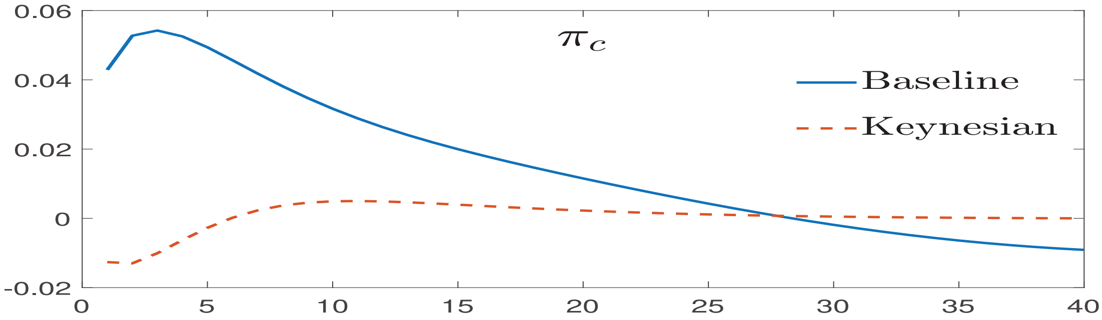


Figure 14: The possible characterization of energy shocks as Keynesian supply shocks. The plot represents the IRFs of the inflation rate in the core sector (π_c) to a positive one standard deviation shock (ε_{p_f}) to the common component of crude energy (p_f), computed at the posterior mean of the estimated parameters (Baseline) and at the parameter configuration that gives Keynesian supply shocks (Keynesian). The IRFs represent percentage deviations from the steady state.

To analyze the relationship between the consumption channel and the production channel, we propose a second exercise where we vary the substitution parameter in consumption (σ_c) and the share of energy in production (s_{m_e,k_c}). Figure 15 shows the response (on impact) of the inflation rate in the core sector (π_c) to a positive shock (ε_{p_f}) to the common component of crude energy (p_f). We consider this particular shock to produce a generalized increase in energy prices and we abstract from shocks that reflect uncertainty in energy commodity markets. The responses are computed under the KSSs parameters (no habits, flexible wages) and with different values of the substitution parameter σ_c (from 0.01, strong complementarity to 1.50, strong substitutability), and different values of the share of energy in production s_{m_e,k_c} (from 0.0001 almost no energy in production, to 0.0156, three times the baseline value). When substitutability is low and the share of energy in production is low, the response of π_c after the energy shock is negative, producing KSSs. In this case, negative demand complementarity outweighs the positive supply effects on core prices generated by energy shocks. In contrast, when demand complementarities are low and the share of energy in production is high, core sector prices increase after the energy shock.

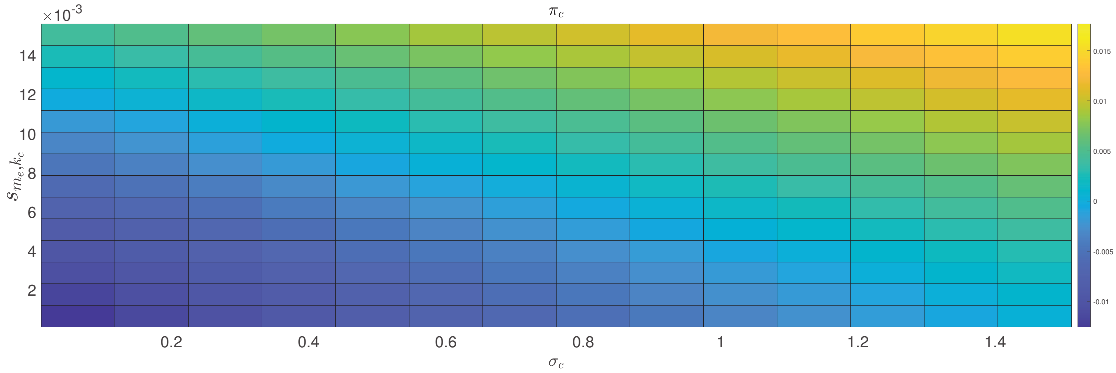


Figure 15: The possible characterization of energy shocks as Keynesian supply shocks. The plot represents the impact response of the inflation rate in the core sector (π_c) to a positive one standard deviation shock (ε_{p_f}) to the common component of crude energy (p_f), computed varying the substitution parameter σ_c and s_{m_e,k_c}. The IRFs represent percentage deviations from the steady state.

Finally, in a third exercise, we use a version of our model which removes capital, intermediate energy in production, habits, nominal rigidities in final goods markets and labor markets, to mimic the Guerrieri et al. (2022) model. Figure 16 reports the response of core sector inflation, for different values of the substitution parameter σ_c (shown in the colorbar). We find that low values of σ_c generate KSSs effects, while high values do not. We do not find KSSs effects in our estimated fully-fledged model, as the presence of real and nominal rigidity and passthrough effects from energy in production rule out Keynesian effects.

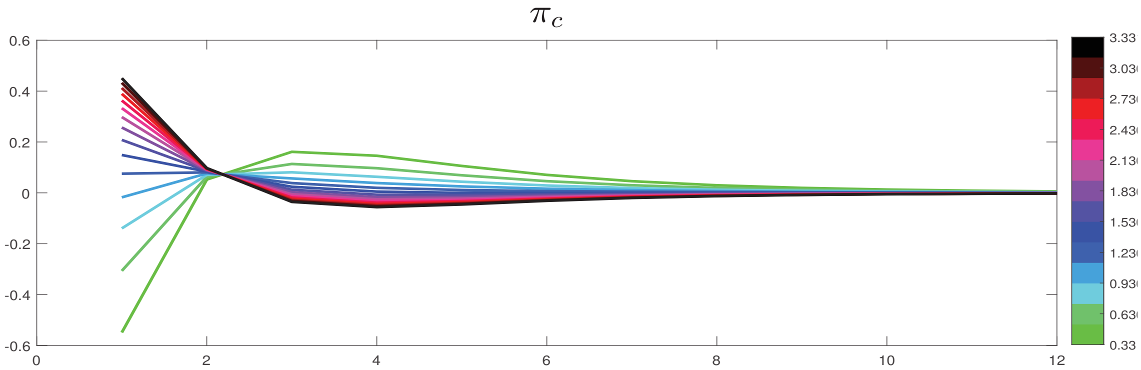


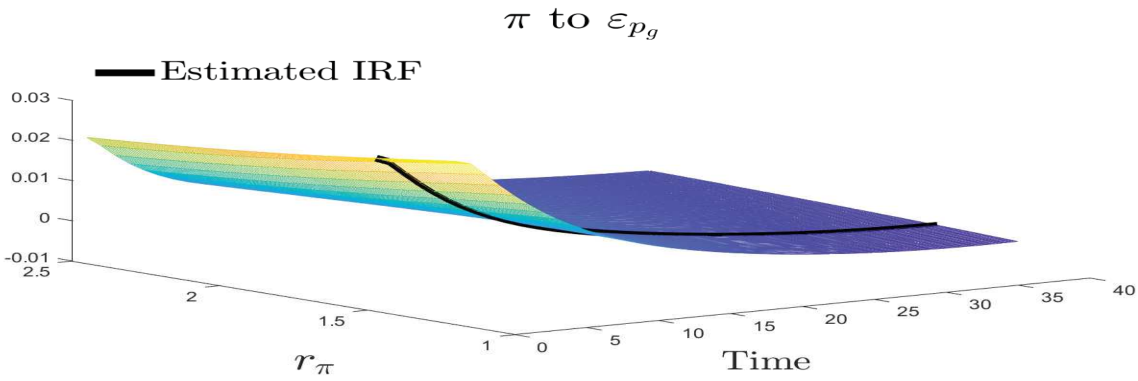
Figure 16: The possible characterization of energy shocks as Keynesian supply shocks in the toy model without capital and all rigidities. The plot represents the IRFs of the inflation in the core sector (π_c) to a positive one standard deviation shock (ε_{p_f}) to the common component of crude energy (p_f), computed with different values of the complementarity parameter σ_c (shown in the colorbar). The IRFs represent percentage deviations from the steady state.

Monetary policy

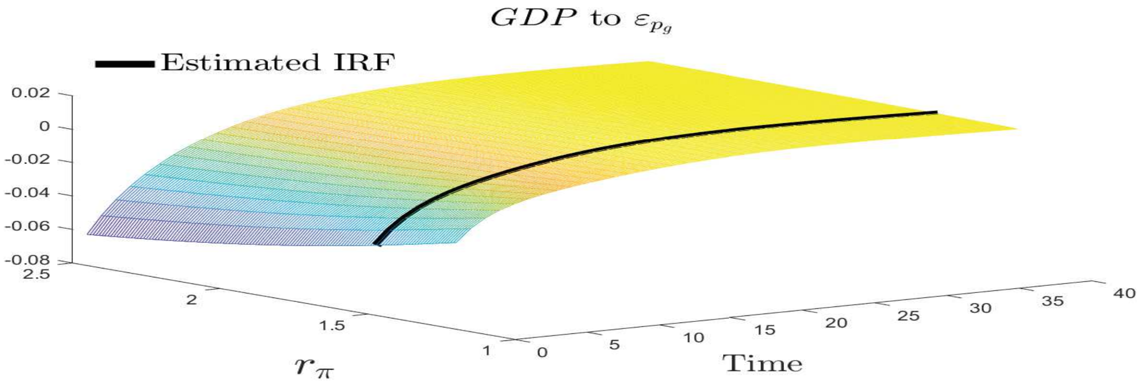
The literature has long recognized the role of monetary policy in amplifying energy shocks, see Bernanke et al. (1997), Leduc and Sill (2004), Blanchard and Gali (2007), Kormilitsina (2011) and Ramey and Vine (2011). As Section 3 shows, the energy sector, despite its modest share in total production, significantly influences inflation dynamics. In this setting, energy shocks indirectly affect GDP by leading to increased interest rates in reaction to elevated prices. In contrast, Bodenstein and Guerrieri (2011) find that monetary policy does not play a substantial role in the transmission of oil price shock, since in their estimated model the majority of oil price fluctuations come from foreign sources.

The top panel of Figure 17, shows the IRF of general inflation (π) to an exogenous increase in the price of natural gas, for different values of the inflation coefficient in the Taylor rule, r_π (from 1.25, loose response, to 2.50, aggressive response). The figure also reports the IRF (solid black line) at our estimated value of $r_\pi = 1.52$. A higher monetary policy response to inflation reduces the inflationary effects of gas price shocks: on impact a looser policy response, $r_\pi = 1.25$, implies an inflation rate (π) that is 46% higher than the response obtained with more aggressive policy, $r_\pi = 2.50$. A tighter inflation control after an increase in the price of gas comes with a higher output loss, as the bottom panel of Figure 17 shows. The negative response of GDP on impact is twice as large when $r_\pi = 2.50$ compared to when $r_\pi = 1.25$. In Appendix E, we show similar results for the response of π and GDP to crude energy shocks and to shocks in the common factor of crude energy prices, for different monetary policies.

Figure 18 shows a counterfactual policy where the interest rate (upper panel) is fixed at the level recorded in 2021:Q4, thereby switching off the subsequent monetary policy tightening. Specifically, we simulate a sequence of monetary policy shocks ($\varepsilon_{e,t}$) that sterilize the observed interest rate hikes realized between 2022:Q1 and 2022:Q4. Considering the end of the reference period (2022:Q4), the general inflation (π) and the core sector inflation (π_c) would be 20 basis points higher under the counterfactual intervention compared to a more restrictive monetary policy. Energy prices are less affected by this policy: in 2022:Q4, the energy inflation rate (π_e) is only two basis points higher than the counterfactual policy. Finally, by the end of 2022, our counterfactual suggests that GDP would be 1% higher than the realized scenario with interest rate hikes.



(a) Inflation



(b) GDP

Figure 17: The impact of monetary policy on the IRFs. The plots represent the IRFs of inflation and GDP to a positive one standard deviation shock to the price of natural gas (ε_{p_g}), varying the degree of responsiveness to inflation of the central bank (r_π). The IRFs represent percentage deviations from the steady state.

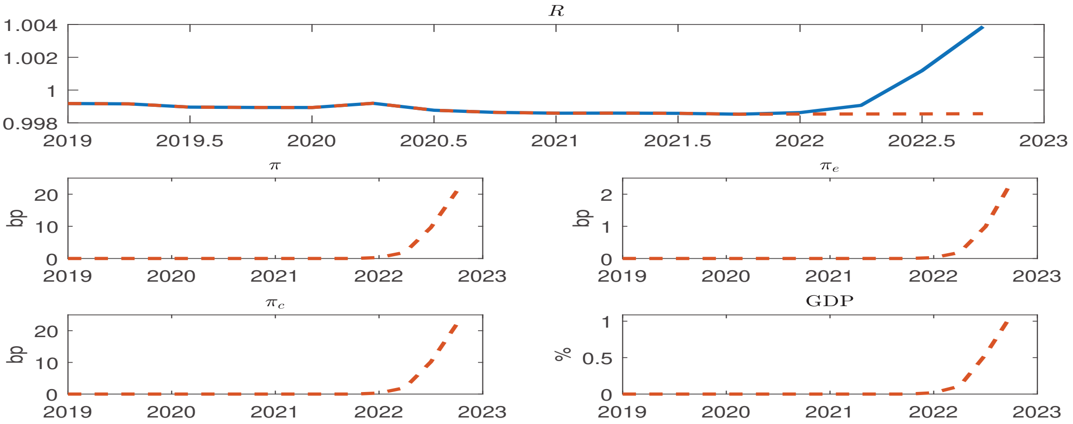


Figure 18: The effects of accommodating monetary policy against energy shocks. The plots represent the nominal interest rate (R), general inflation (π), energy inflation (π_e), core inflation (π_c) and the level of real gross domestic product (GDP). Dashed red lines in the last four smaller plots represent differences of the variables in the case of monetary policy intervention to the case of no monetary policy intervention, measured in basis points for the inflation rates and in percentage points for GDP.

Fiscal policy

We now consider a fiscal policy that provides relief to refined energy users affected by the increase in energy prices. The fiscal authority introduces a subsidy ($\tau_{e,t}$) that reduces the price of energy paid for by households and firms in the core sector. In this setting, the fiscal authority runs a balanced budget by imposing a lump-sum tax (T_t) on households to finance energy subsidies. The budget constraint of households (see eq. 13) becomes:

$$\begin{aligned} c_{c,t} + (1-\tau_{e,t})\, p_{e,t} c_{e,t} + \frac{i_{c,t}}{a_{k,t}} + p_{e,t}\frac{i_{e,t}}{a_{k,t}} + b_t = & \frac{R_{t-1} b_{t-1}}{\pi_{c,t}} + \frac{w_{c,t} n_{c,t}}{X_{w_c,t}} + p_{e,t}\frac{w_{e,t} n_{e,t}}{X_{w_e,t}} \\ & + r_{k_c,t} u_{k_c,t} k_{c,t-1} + p_{e,t} r_{k_e,t} u_{k_e,t} k_{e,t-1} \\ & + \Pi_t - \frac{\Psi_t}{a_{k,t}} + p_{e,t} p_{v,t} V_{e,t} - T_t, \end{aligned}$$

and the profit function of core sector firms (see eq. 8) becomes:

$$\max \frac{Y_{c,t}}{X_{c,t}} - w_{c,t} n_{c,t} - r_{k_c,t} u_{k_c,t} k_{c,t-1} - (1-\tau_{e,t})\, p_{e,t} m_{e,t}.$$

The subsidy $\tau_{e,t}$ is an exogenous process that is set by the fiscal authority as an AR process:

$$\tau_{e,t} = \rho_{\tau_e} \tau_{e,t-1} + \varepsilon_{\tau_e,t},$$

where ρ_{τ_e} is the persistence of the subsidy and $\varepsilon_{\tau_{e},t}$ is the innovation in the process, representing new policy interventions. The expression for the lump-sum tax (T_t) is:

$$T_t = \tau_{e,t} p_{e,t} m_{e,t} + \tau_{e,t} p_{e,t} c_{e,t}. \tag{20}$$

In the analysis, we assume that the fiscal authority follows a path of interventions that keeps the price of energy at the 2021:Q1 level (t^*). This is achieved by incrementally raising the subsidy rate to sterilize price hikes. We assume a persistent value for the AR(1) parameter ($\rho_{\tau_e} = 0.99$), which means that the policy is perceived as long-lasting (but there is no expectation that the fiscal authority will offset future hikes in energy prices).

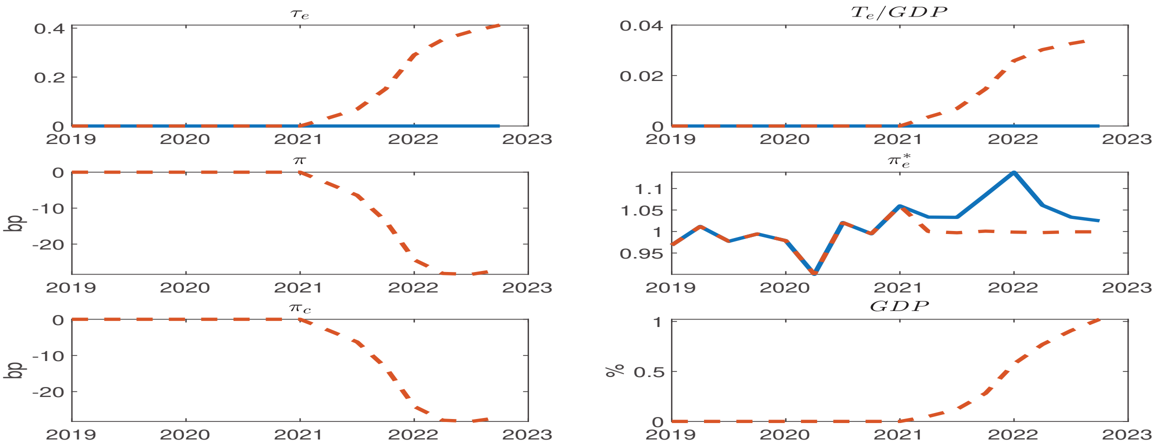


Figure 19: The effects of fiscal policy against energy shocks. The plots represent the subsidy rate ($\tau_{e,t}$), the ratio between the lump-sum tax and gross domestic product (T_e/GDP), general inflation (π), effective energy price inflation ($\pi_e^* \equiv [p_{e,t}(1-\tau_{e,t})]/[p_{e,t-1}(1-\tau_{e,t-1})]$), core inflation ($\pi_c$) and the level of real gross domestic product (GDP). Solid blue lines in the plots of τ_e, T_e/GDP and π_e^* represent the smoothed quantities when no subsidy shock is simulated. The dashed red lines represent the variables when the energy subsidy policy is active. Dashed red lines in the graphs of π, π_c, and GDP indicate difference in the variables between the cases where the subsidy program is in effect and the scenario where it is not.

Figure 19 shows the evolution of selected model variables under both active and inactive energy subsidy policy scenarios. For comparability with the monetary policy exercise, we plot the same variables of Figure 18, except for the policy variables in the first row (the subsidy rate and the lump-sum tax). The subsidy rate ($\tau_{e,t}$) must increase by 41% to offset the increase in the energy price accumulated in 2022:Q4 (first panel). The increase in expenditure by the fiscal authority requires a lump-sum tax ($T_{e,t}$), which amounts to 3.5% of GDP in 2022:Q4 (second panel). The fourth panel shows that these subsidies are designed to neutralize energy price inflation, $\pi_{e,t}^* \equiv \frac{p_{e,t}(1-\tau_{e,t})}{p_{e,t-1}(1-\tau_{e,t-1})}$, (red dashed line) rather than the large and positive inflation observed in the data (blue solid line). These subsidies are distortionary, as they influence the first-order conditions of households and firms, and consequently shift the demand for energy. Lower energy prices mitigate the reduction in the demand for energy from firms and households ($m_{e,t}$ and $c_{e,t}$), generating a positive effect on GDP (last panel) through the production and consumption channels. The higher energy demand in consumption ($c_{e,t}$) and in production ($m_{e,t}$) increases GDP by 1% in 2022:Q4, compared to the no-subsidy scenario. Figure 19 shows that fiscal intervention decreases the general inflation rate (π) and the core sector inflation rate (π_c) with respect to the no-intervention scenario.

We compare the economic gains resulting from this policy (increases in GDP) with its costs (increases in taxes), quantifying the fiscal multipliers (Mountford and Uhlig, 2009 and Zubairy, 2014):

$$M_{\tau_e,h} = \frac{\mathbb{E}_t \sum_{i=0}^{h} \left(\frac{1}{R_{t|t+i}}\right) \Delta GDP_{t+i}}{\mathbb{E}_t \sum_{i=0}^{h} \left(\frac{1}{R_{t|t+i}}\right) \Delta T_{t+i}}, \tag{21}$$

where the discount factor is given by the product of risk-free gross policy rates from t to $t+i$:

$$R_{t|t+i} = \prod_{j=0}^{i} R_{t+j}.$$

In eq. (21), at each period i after the shock, we compute (a) the GDP gains when the shock to the subsidy rate ($\varepsilon_{\tau_e,t}$) occurs with respect to the case when it does not (ΔGDP_{t+i}) and (b) the corresponding increases in the subsidy which, assuming a balanced budget as in eq. (20), equal the increase in taxes (ΔT_{t+i}).

Figure 20 shows the cumulative fiscal multipliers, computed for each period h after the shock. $M_{\tau_e,h}$ is positive on impact (20%) and then increases monotonically to around 46% in the long run. Multipliers never exceed unity, indicating that the discounted sum of GDP gains does not exceed the discounted sum of increases in the subsidy at any time horizon. Our model does not consider features that could increase the effectiveness of the energy subsidy, such as imperfect consumption smoothing by debt-constrained households that benefit the most from the relief policy (Bhattarai and Trzeciakiewicz, 2017).[23]

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[23] At the same time, introducing constraints on public finance could reduce the effectiveness of this policy.

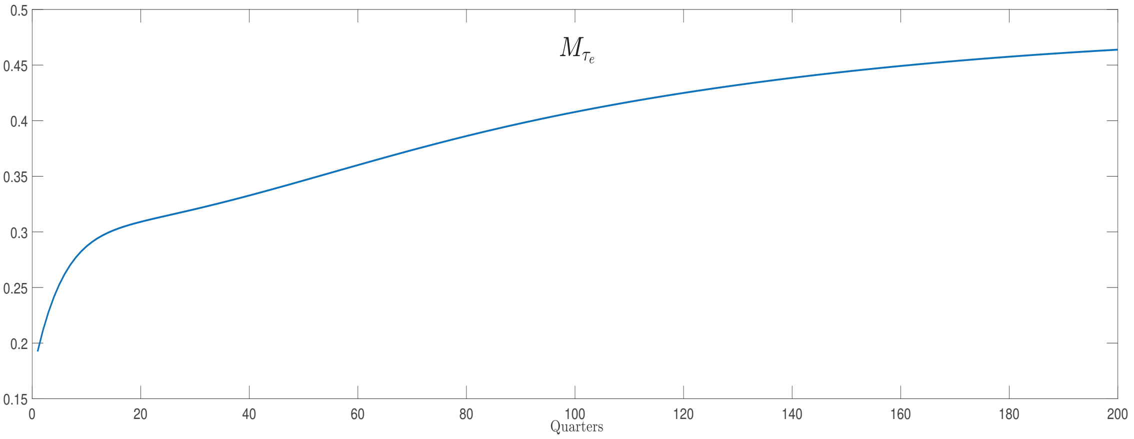

Figure 20: Fiscal multipliers. The line represents the cumulative multipliers associated with the subsidy policy. The horizontal axis represents the number of quarters after the shock to the subsidy rate (ε_{τ_e}) realizes.

5 Conclusion

The paper proposes a two-sector macroeconomic model with an energy sector that uses crude energy sources (coal, oil and gas) to produce refined energy for a core sector and households. The model is estimated using EA data that cover the increases in energy prices that occurred after the COVID-19 pandemic. We distinguish between the contribution of the pandemic recession and rebound shocks and the contribution of the energy shocks of 2021-2022.

Pandemic shocks significantly impact the energy markets, determining 70% of the increase in energy prices recorded between 2021:Q1 and 2022:Q4; the rest is accounted by energy shocks. Concerning the general price level, we find that energy shocks explain 32% of the price change observed between 2021:Q1 and 2022:Q4. We also find that oil and gas are the most important contributors to price movements, while coal accounts for around 15%. Our structural model considers the role of various economic channels in the transmission of energy shocks. We find that complementarities in the use of energy, inertia in labor markets, and monetary policy are relevant factors that amplify the impact of energy shocks. The estimated nominal and real rigidities and the presence of energy in production, lead to higher core sector prices, ruling out the Keynesian transmission of these shocks.

We also evaluate how fiscal policy can mitigate the effects of energy shocks. Given the representative agent setup of our model, we find that the multipliers of these interventions are below one. Future research with a model in which households are not completely able to smooth consumption over time may add new insights into the role of fiscal policy. Future investigations will also benefit from explicitly introducing green energy sources into the model and evaluating the effects of recent energy shocks in accelerating or delaying the green transition.

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Supplementary Material for "Energy Shocks, Pandemics and the Macroeconomy"

Luisa Corrado, Stefano Grassi, Aldo Paolillo and Francesco Ravazzolo.

A The Model Equations

Wholesale Energy Sector Firms

We show here the first-order conditions of the wholesale firms in the energy sector.

- Labor Demand:

$$\frac{1}{X_{e,t}}\frac{(1-\alpha_e)Y_{e,t}}{n_{e,t}} = w_{e,t}. \tag{22}$$

- Raw capital demand:

$$\frac{1}{X_{e,t}}\frac{\alpha_e \omega_{k_e} Y_{e,t}}{k_{e,t-1}} = r_{k_e,t} u_{k_e,t}. \tag{23}$$

- Crude oil demand:

$$\frac{1}{X_{e,t}}\frac{\alpha_e(1-\omega_{k_e})Y_{e,t}}{V_{e,t}} a_{V_o,t}\omega_o^{\frac{1}{\sigma_v}}\left(\frac{V_{e,t}}{V_{o,t}}\right)^{\frac{1}{\sigma_v}} = p_{o,t}. \tag{24}$$

- Natural gas demand:

$$\frac{1}{X_{e,t}}\frac{\alpha_e(1-\omega_{k_e})Y_{e,t}}{V_{e,t}} a_{V_g,t}\omega_g^{\frac{1}{\sigma_v}}\left(\frac{V_{e,t}}{V_{g,t}}\right)^{\frac{1}{\sigma_v}} = p_{g,t}. \tag{25}$$

- Coal demand:

$$\frac{1}{X_{e,t}}\frac{\alpha_e(1-\omega_{k_e})Y_{e,t}}{V_{e,t}} a_{V_c,t}\left(1-\omega_o-\omega_g\right)^{\frac{1}{\sigma_v}}\left(\frac{V_{e,t}}{V_{c,t}}\right)^{\frac{1}{\sigma_v}} = p_{c,t}. \tag{26}$$

Retail Energy Sector Firms

The problem faced by the retail energy firm is to set the retail price $P_{e,t}(j)$ to maximize profits minus the quadratic adjustment costs *à la* Rotemberg (depending on the rigidity parameter η_{π_e}). Moreover, the quadratic adjustment costs depend on the inflation of the last quarter, and the relative weight is given by the indexation parameter ι_{π_e}:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{u_{c_c,t}}{u_{c_c,0}} \left[\frac{P_{e,t}(j)}{P_{e,t}} Y_{e,t}(j) - \frac{1}{X_{e,t}} Y_{e,t}(j) - \frac{\eta_{\pi_e}}{2} \left(\frac{P_{e,t}(j)}{P_{e,t-1}(j)} - \pi_{e,t-1}^{\iota_{\pi_e}} \right)^2 Y_{e,t} \right] \right\}, \quad (27)$$

subject to:

$$Y_{e,t}(j) = \left(\frac{P_{e,t}(j)}{P_{e,t}} \right)^{-\epsilon_{\pi_e}} Y_{e,t}.$$

This optimization problem shows that deviations in the prices of individual varieties $\left(\frac{P_{e,t}(j)}{P_{e,t-1}(j)}\right)$ from past inflation $(\pi_{e,t-1}^{\iota_{\pi_e}})$ are penalized, depending on the rigidity parameters η_{π_e}. Moreover, as eq. (27) shows, at each time t the profits of retailers are weighted by the stochastic discount rate $\left(\beta^t \frac{u_{c_c,t}}{u_{c_c,0}}\right)$, which depends on the marginal utility of consumption at time t. For fully flexible prices ($\eta_{\pi_e} = 0$), the markup is set at its steady-state value $X_e = \frac{\epsilon_{\pi_e}}{\epsilon_{\pi_e} - 1}$. The profits of retailers in the energy sector are:

$$\Pi_{r_e,t} = \left(1 - \frac{1}{X_{e,t}}\right) Y_{e,t} - \frac{\eta_{\pi_e}}{2} \left(\pi_{e,t} - \pi_{e,t-1}^{\iota_{\pi_e}}\right)^2 Y_{e,t}.$$

The solution to the optimization problem of the retail energy firms produces the following price Phillips curve:

$$\begin{aligned} & 1 - \pi_{e,t}\eta_{\pi_e} \left(\pi_{e,t} - \pi_{e,t-1}^{\iota_{\pi_e}}\right) + \beta \eta_{\pi_e} \mathbb{E}_t \left[\pi_{e,t+1} \frac{u_{c_c,t+1}}{u_{c_c,t}} \left(\pi_{e,t+1} - \pi_{e,t-1}^{\iota_{\pi_e}}\right) \frac{Y_{e,t+1}}{Y_{e,t}} \right] \\ & = \left(1 - \frac{1}{X_{e,t}}\right) \epsilon_{\pi_e}. \end{aligned} \quad (28)$$

Wholesale Core Sector Firms

The maximization of the profit function by the core sector wholesalers gives the following demand schedules for the inputs in production:

- Labor Demand:

$$\frac{1}{X_{c,t}} \frac{(1-\alpha_c) Y_{c,t}}{n_{c,t}} = w_{c,t}. \quad (29)$$

- Raw capital demand:

$$\frac{1}{X_{c,t}} \frac{\alpha_c Y_{c,t}}{\bar{k}_{c,t}} \omega_{k_c}^{\frac{1}{\sigma_{k_c}}} \left(\frac{\bar{k}_{c,t}}{k_{c,t-1}} \right)^{\frac{1}{\sigma_{k_c}}} = r_{k_c,t} u_{k_c,t}. \quad (30)$$

- Energy demand:

$$\frac{1}{X_{c,t}}\frac{\alpha_c Y_{c,t}}{\bar{k}_{c,t}}\left(1-\omega_{k_c}\right)^{\frac{1}{\sigma_{k_c}}}\left(\frac{\bar{k}_{c,t}}{m_{e,t}}\right)^{\frac{1}{\sigma_{k_c}}}=p_{e,t}. \tag{31}$$

Retail Core Sector Firms

Retailers in the core sector face quadratic adjustment costs *à la* Rotemberg (depending on the rigidity parameter η_{π_c} and the indexation parameter ι_{π_c}), similarly to the energy sector. Specifically, the problem of the retail core sector firm is to set $P_{c,t}(j)$ to maximize:

$$\mathbb{E}_0\sum_{t=0}^{\infty}(\beta)^t\left\{\frac{u_{c_c,t}}{u_{c_c,0}}\left[\frac{P_{c,t}(j)}{P_{c,t}}Y_{c,t}(j)-\frac{1}{X_{c,t}}Y_{c,t}(j)-\frac{\eta_{\pi_c}}{2}\left(\frac{P_{c,t}(j)}{P_{c,t-1}(j)}-\pi_{c,t-1}^{\iota_{\pi_c}}\right)^2Y_{c,t}\right]\right\}, \tag{32}$$

subject to

$$Y_{c,t}(j)=\left(\frac{P_{c,t}(j)}{P_{c,t}}\right)^{-\epsilon_{\pi_c}}Y_{c,t}.$$

This optimization problem shows that deviations of the prices of varieties $\left(\frac{P_{c,t}(j)}{P_{c,t-1}(j)}\right)$ from past inflation ($\pi_{c,t-1}^{\iota_{\pi_c}}$) are penalized, depending on the rigidity parameters η_{π_c}. Moreover, as eq. (32) shows, at each time t retailers' profits are weighted by the stochastic discount rate $\left(\beta^t\frac{u_{c_c,t}}{u_{c_c,0}}\right)$, which depends on the marginal utility of consumption at time t. The solution to the optimization problem of the retail core firms gives the price Phillips curve is the following:

$$\begin{aligned}&1-\pi_{c,t}\eta_{\pi_c}\left(\pi_{c,t}-\pi_{c,t-1}^{\iota_{\pi_c}}\right)+\beta\eta_{\pi_c}\mathbb{E}_t\left[\pi_{c,t+1}\frac{u_{c_c,t+1}}{u_{c_c,t}}\left(\pi_{c,t+1}-\pi_{c,t-1}^{\iota_{\pi_c}}\right)\frac{Y_{c,t+1}}{Y_{c,t}}\right]\\&=\left(1-\frac{1}{X_{c,t}}\right)\epsilon_{\pi_c}.\end{aligned} \tag{33}$$

The expression for the profits of the core sector's retailers is the following:

$$\Pi_{r_c,t}=\left(1-\frac{1}{X_{c,t}}\right)Y_{c,t}-\frac{\eta_{\pi_c}}{2}\left(\pi_{c,t}-\pi_{c,t-1}^{\iota_{\pi_c}}\right)^2Y_{c,t}.$$

Unions

We report here the maximization problem faced by labor unions in the two sectors. Labor unions face the demand schedules $n_{i,t}(j)=\left(\frac{W_{i,t}(j)}{W_{i,t}}\right)^{-\epsilon_w}n_{i,t}$, $i\in\{c,e\}$, and pay quadratic adjustment costs *à la* Rotemberg for wage changes. The quadratic adjustment costs depend on the inflation of the previous quarter, with weight given by the indexation parameter ι_w:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ u_{c_c,t} \left[\frac{W_{i,t}(j)}{P_{i,t}} n_{i,t}(j) - \frac{\eta_w}{2} \left(\frac{W_{i,t}(j)}{W_{i,t-1}(j)} - \pi_{i,t-1}^{\iota_w} \right)^2 \frac{W_{i,t}}{P_{i,t}} \right] \right. \\ \left. - \frac{a_{\zeta,t} \varphi^i a_{\varphi,t} n_{i,t}(j)^{1+\nu_i}}{1+\nu_i} \right\}.$$

The maximization gives the two wage Phillips curves:

- Wage Phillips curve for $\mathcal{S}_c$:

$$\begin{aligned} \eta_w \omega_{c,t} \left(\omega_{c,t} - \pi_{c,t-1}^{\iota_w} \right) = {} & \beta \eta_w \mathbb{E}_t \frac{u_{c_c,t+1}}{u_{c_c,t}} \left(\omega_{c,t+1} - \pi_{c,t}^{\iota_w} \right) \frac{\omega_{c,t+1}^2}{\pi_{c,t+1}} \\ & + (1-\epsilon_w) n_{c,t} + \epsilon_w \left(\frac{\varphi^c a_{\varphi,t}, n_{c,t}^{1+\nu_c}}{w_{c,t} u_{c_c,t}} \right). \end{aligned} \tag{34}$$

- Wage Phillips curve for $\mathcal{S}_e$:

$$\begin{aligned} \eta_w \omega_{e,t} \left(\omega_{e,t} - \pi_{e,t-1}^{\iota_w} \right) = {} & \beta \eta_w \mathbb{E}_t \frac{u_{c_c,t+1}}{u_{c_c,t}} \left(\omega_{e,t+1} - \pi_{e,t}^{\iota_w} \right) \frac{\omega_{e,t+1}^2}{\pi_{e,t+1}} \\ & + (1-\epsilon_w) n_{e,t} + \epsilon_w \left(\frac{\varphi^e a_{\varphi,t}, n_{e,t}^{1+\nu_e}}{w_{e,t} u_{c_c,t}} \right). \end{aligned} \tag{35}$$

Above, $\omega_{c,t}$ and $\omega_{e,t}$ are the nominal wage inflation rates, namely $\omega_{i,t} = \frac{W_{i,t}}{W_{i,t-1}} = \frac{P_{i,t} w_{i,t}}{P_{i,t-1} w_{i,t-1}} = \pi_{i,t} \frac{w_{i,t}}{w_{i,t-1}}$. Profits of unions are given by net margins minus adjustment costs:

$$\Pi_{u_c,t} = \left(1 - \frac{1}{X_{w_c,t}} \right) w_{c,t} \, n_{c,t} - \frac{\eta_w}{2} \left(\omega_{c,t} - \pi_{c,t-1}^{\iota_w} \right)^2 w_{c,t} n_{c,t},$$

$$\Pi_{u_e,t} = \left(1 - \frac{1}{X_{w_e,t}} \right) w_{e,t} \, n_{e,t} - \frac{\eta_w}{2} \left(\omega_{e,t} - \pi_{e,t-1}^{\iota_w} \right)^2 w_{e,t} \, n_{e,t}.$$

The term Π_t, appearing in the household's budget constraint (eq. 13) is then given by:

$$\Pi_t = \Pi_{u_c,t} + p_{e,t} \Pi_{u_e,t} + \Pi_{r_c,t} + p_{e,t} \Pi_{r_e,t}.$$

The sum of all nominal adjustment costs of the two sectors appearing in the market clearing (17) and (18) are finally given by:

$$\begin{aligned} \Xi_{c,t} &= \Xi_{\pi_c,t} + \Xi_{w_c,t} \\ &= \left[\frac{\eta_{\pi_c}}{2} \left(\pi_{c,t} - \pi_{c,t-1}^{\iota_{\pi_c}} \right)^2 \right] Y_{c,t} + \frac{\eta_w}{2} \left(\omega_{c,t} - \pi_{c,t-1}^{\iota_w} \right)^2 w_{c,t} n_{c,t}, \end{aligned} \tag{36}$$

and

$$\begin{aligned}\Xi_{e,t} &= p_{e,t}\Xi_{\pi_e,t} + p_{e,t}\Xi_{w_e,t} \\ &= \left[\frac{\eta_{\pi_e}}{2}\left(\pi_{e,t} - \pi_{e,t-1}^{\iota_{\pi_e}}\right)^2\right] p_{e,t}Y_{e,t} + \frac{\eta_w}{2}\left(\omega_{e,t} - \pi_{e,t-1}^{\iota_w}\right)^2 p_{e,t}w_{e,t}n_{e,t}.\end{aligned} \tag{37}$$

Households

The functional forms of the investment and capacity utilization costs appearing in the household's budget constraint (eq. 13) are the following:

$$\Psi_{k_c,t} = \frac{\eta_k}{2}\left(\frac{k_{c,t}}{k_{c,t-1}} - 1\right)^2 k_{c,t-1}, \qquad \Psi_{k_e,t} = \frac{\eta_k}{2}\left(\frac{k_{e,t}}{k_{e,t-1}} - 1\right)^2 k_{e,t-1},$$

$$\Psi_{u_c,t} = \left[\frac{1}{\beta} - (1-\delta_{k_c})\right]\left[\frac{\left(\frac{\eta_u}{1-\eta_u}\right)}{2} + \frac{\left(\frac{\eta_u}{1-\eta_u}\right)}{2}u_{k_c,t}^2 + u_{k_c,t}\left(1 - \frac{\eta_u}{1-\eta_u}\right) - 1\right],$$

$$\Psi_{u_e,t} = \left[\frac{1}{\beta} - (1-\delta_{k_e})\right]\left[\frac{\left(\frac{\eta_u}{1-\eta_u}\right)}{2} + \frac{\left(\frac{\eta_u}{1-\eta_u}\right)}{2}u_{k_e,t}^2 + \left(1 - \frac{\eta_u}{1-\eta_u}\right)u_{k_e,t} - 1\right].$$

The term Ψ_t in the household's budget constraint (eq. 13) is then given by:

$$\Psi_t = \Psi_{k_c,t} + p_{e,t}\Psi_{k_e,t} + \Psi_{u_c,t}k_{c,t-1} + p_{e,t}\Psi_{u_e,t}k_{e,t-1}.$$

The optimization of the households leads to the following first-order conditions:

- Euler equation:

$$u_{c_c,t} = \beta R_t \mathbb{E}_t\left(\frac{u_{c_c,t+1}}{\pi_{c,t+1}}\right).$$

- Intratemporal consumption condition:

$$\frac{u_{c_e,t}}{p_{e,t}} = u_{c_c,t}. \tag{38}$$

  where the marginal utilities of consumption of non-energy ($u_{c_c,t}$) and energy goods ($u_{c_e,t}$) are defined by:

- Marginal utility of non-energy goods:

$$u_{c_c,t} = \frac{1-h}{1-\beta h}\left[\frac{a_{\zeta,t}}{\bar{c}_t - h\bar{c}_{t-1}} - \mathbb{E}_t\frac{h\beta a_{\zeta,t+1}}{\bar{c}_{t+1} - h\bar{c}_t}\right]\left[\frac{\bar{c}_t}{c_{c,t}}\right]^{\frac{1}{\sigma_c}}\omega_{c_c}^{\frac{1}{\sigma_c}}. \tag{39}$$

- Marginal utility of energy goods:

$$u_{c_e,t} = \frac{1-h}{1-\beta h}\left[\frac{a_{\zeta,t}}{\bar{c}_t - h\bar{c}_{t-1}} - \mathbb{E}_t\frac{h\beta a_{\zeta,t+1}}{\bar{c}_{t+1} - h\bar{c}_t}\right]\left[\frac{\bar{c}_t}{c_{e,t}}\right]^{\frac{1}{\sigma_c}}(1-\omega_{c_c})^{\frac{1}{\sigma_c}}a_{j,t}^{\frac{1}{\sigma_c}}. \tag{40}$$

- Labor supply to $\mathcal{S}_c$:

$$a_{\zeta,t}a_{\varphi,t}\varphi^c n_{c,t}^{\nu_c} = \frac{w_{c,t}u_{c_c,t}}{X_{w_c,t}}.$$

- Labor supply to $\mathcal{S}_e$:

$$a_{\zeta,t}a_{\varphi,t}\varphi^e n_{e,t}^{\nu_e} = \frac{p_{e,t}w_{e,t}u_{c_c,t}}{X_{w_e,t}}.$$

- Capital supply to $\mathcal{S}_c$:

$$\begin{aligned}&u_{c_c,t}\left[1+\eta_k\left(\frac{k_{c,t}}{k_{c,t-1}}-1\right)\right]\frac{1}{a_{k,t}}\\ &=\beta\mathbb{E}_t u_{c_c,t+1}\left[r_{k_c,t+1}u_{k_c,t+1} + (1-\delta_{k_c})\frac{1}{a_{k,t+1}} - \Psi_{u_c,t+1}\frac{1}{a_{k,t+1}} + \frac{\eta_k}{2}\left(\frac{k_{c,t+1}^2}{k_{c,t}^2}-1\right)\frac{1}{a_{k,t+1}}\right].\end{aligned}$$

- Capital supply to $\mathcal{S}_e$:

$$\begin{aligned}&p_{e,t}u_{c_e,t}\left[1+\eta_k\left(\frac{k_{e,t}}{k_{e,t-1}}-1\right)\right]\frac{1}{a_{k,t}}\\ &=\beta\mathbb{E}_t p_{e,t+1}u_{c_e,t+1}\left[r_{k_e,t+1}u_{k_e,t+1} + (1-\delta_{k_e})\frac{1}{a_{k,t+1}} - \Psi_{u_e,t+1}\frac{1}{a_{k,t+1}} + \frac{\eta_k}{2}\left(\frac{k_{e,t+1}^2}{k_{e,t}^2}-1\right)\frac{1}{a_{k,t+1}}\right].\end{aligned}$$

- Capacity utilization in $\mathcal{S}_c$ condition:

$$\frac{r_{k_c,t}}{\frac{1}{\beta}-(1-\delta_{k_c})} = 1 - \frac{\eta_u}{1-\eta_u} + \frac{\eta_u}{1-\eta_u}u_{k_c,t}. \tag{41}$$

- Capacity utilization in $\mathcal{S}_e$ condition:

$$\frac{r_{k_e,t}}{\frac{1}{\beta}-(1-\delta_{k_e})} = 1 - \frac{\eta_u}{1-\eta_u} + \frac{\eta_u}{1-\eta_u}u_{k_e,t}. \tag{42}$$

B Steady State

In this section we derive the steady state of the model. Variables without the time subscript denote steady-state values.

The hours worked in the two sectors are set to the desired targets n_c^{ss} and n_e^{ss}:

$$n_c = n_c^{ss}, \qquad n_e = n_e^{ss}.$$

The Phillips curves eqs. (33), (28), (34) and (35) determine the markups in steady state:

$$X_c = \frac{\epsilon_{\pi_c}}{\epsilon_{\pi_c} - 1}, \qquad X_e = \frac{\epsilon_{\pi_e}}{\epsilon_{\pi_e} - 1}, \qquad X_{w_c} = \frac{\epsilon_w}{\epsilon_w - 1}, \qquad X_{w_e} = \frac{\epsilon_w}{\epsilon_w - 1}.$$

The model is solved around a zero-inflation equilibrium, where the interest rate equals the inverse of the discount rate. Moreover, utilization rates are normalized to one in steady state and all adjustment costs are zero, namely:

$$\pi_c = 1, \qquad \pi_e = 1, \qquad \omega_c = 1, \qquad \omega_e = 1,$$

$$R = R_{ss} = \frac{1}{\beta},$$

$$u_{k_c} = 1, \qquad u_{k_e} = 1,$$

$$\Psi_{k_e} = 0, \qquad \Psi_{k_c} = 0, \qquad \Psi_{u_e} = 0, \qquad \Psi_{u_c} = 0, \qquad \Xi_c = 0, \qquad \Xi_e = 0.$$

We impose that the relative price of energy is equal to one in steady state:

$$p_e = 1.$$

The capacity utilization eqs. (41) and (42) determine the capital rental rates in steady state:

$$r_{k_c} = \frac{1}{\beta} - 1 + \delta_{k_c}, \qquad r_{k_e} = \frac{1}{\beta} - 1 + \delta_{k_e}.$$

We impose that the relative prices of oil, gas and coal are equal to the desired targets (see Table 1):

$$p_o = p_o^{ss}, \qquad p_g = p_g^{ss}, \qquad p_c = p_c^{ss}.$$

From the demand for raw capital by the core sector (eq. 30) and the demand for refined energy (eq. 31), it is possible to derive the expression for the share parameter ω_{k_c} as a function of the calibration target $s_{m_e,k_c} \equiv \frac{m_e}{k_c}$:

$$\omega_{k_c} = \left(1 + s_{m_e,k_c} r_{k_c}^{-\sigma_{k_c}}\right)^{-1}.$$

We define the price index ($\bar{r}_{k_c}$) for the CES composite ($\bar{k}_c$) of raw capital and refined energy in the core sector:

$$\bar{r}_{k_c} = \left[\omega_{k_c} r_{k_c}^{1-\sigma_{k_c}} + (1-\omega_{k_c}) p_e^{1-\sigma_{k_c}}\right]^{\frac{1}{1-\sigma_{k_c}}}.$$

In steady state, the demand for $\bar{k}_c$ from the core sector implies the following ratio:

$$\zeta_1 \equiv \frac{\bar{k}_c}{Y_c} = \alpha_c \frac{1}{X_c} \frac{1}{\bar{r}_{k_c}}.$$

Using the production function in eq. (9), this allows to find Y_c, and $\bar{k}_c$:

$$Y_c = n_c \zeta_1^{\frac{\alpha_c}{1-\alpha_c}}, \qquad \bar{k}_c = \zeta_1 Y_c.$$

Using the demand for raw capital (k_c) and the demand for refined energy (m_e) by the core sector, it is possible to find the ratio between these two inputs:

$$\zeta_4 \equiv \frac{m_e}{k_c} = \left[r_{k_c} \frac{1}{p_e} (1-\omega_{k_c})^{\frac{1}{\sigma_{k_c}}} \frac{1}{\omega_{k_c}^{\frac{1}{\sigma_{k_c}}}} \right]^{\sigma_{k_c}}.$$

Using eq. (10), we find k_c and then m_e:

$$k_c = \bar{k}_c \left[\omega_{k_c}^{\frac{1}{\sigma_{k_c}}} + (1-\omega_{k_c})^{\frac{1}{\sigma_{k_c}}} \zeta_4^{\frac{\sigma_{k_c}-1}{\sigma_{k_c}}} \right]^{\frac{\sigma_{k_c}}{1-\sigma_{k_c}}},$$

$$m_e = \zeta_4 k_c.$$

The productivities of crude energy sources are equal to one in steady state:

$$a_{V_o} = 1, \qquad a_{V_g} = 1, \qquad a_{V_c} = 1.$$

Furthermore, the exogenous processes in steady state are equal to their unconditional mean:

$$a_j = 1, \quad a_\zeta = 1, \quad a_\varphi = 1, \quad a_{z_c} = 1, \quad a_r = 1, \quad a_k = 1, \quad a_{z_e} = 1.$$

Using the definition of the composite of crude energy (V_e) in eq. (3) and its price index in eq. (4), p_v, it follows that the demand for crude energy (V_e) by the energy sector is:

$$\alpha_e (1 - \omega_{k_e}) \frac{Y_e}{V_e} = p_v.$$

It also holds that the share parameter ω_{k_e} must satisfy the following relationship to match the calibration target $s_{p_v V_e, Y_e} \equiv \frac{p_v V_e}{Y_e}$:

$$\omega_{k_e} = 1 - s_{p_v V_e, Y_e} \frac{1}{\alpha_e} X_e.$$

From the demand for oil, gas and coal by the energy sector (eqs. 24, 25 and 26), we find the following relationships:

$$\omega_g = \omega_o \left(\frac{p_g}{p_o} \right)^{\sigma_v} s_{Vg,Vo}, \tag{43}$$

$$1 - \omega_o - \omega_g = \omega_o \left(\frac{p_c}{p_o} \right)^{\sigma_v} s_{Vc,Vo}. \tag{44}$$

Summing eq. (43) and (44), it is possible to find that ω_o must be set in the following way to respect the calibration targets:

$$\omega_o = \left[1 + s_{V_g,V_o} \left(\frac{p_g}{p_o} \right)^{\sigma_v} s_{V_c,V_o} \left(\frac{p_c}{p_o} \right)^{\sigma_v} \right]^{-1},$$

and from eq. (43) that ω_g must be set in the following way:

$$\omega_g = \omega_o \left[s_{V_g,V_o} \left(\frac{p_g}{p_o} \right)^{\sigma_v} \right].$$

Using ω_o and ω_g, we obtain the price index of crude energy sources:

$$p_v = \left[\omega_o p_o^{1-\sigma_v} + \omega_g p_g^{1-\sigma_v} + (1 - \omega_o - \omega_g) p_c^{1-\sigma_v} \right]^{\frac{1}{1-\sigma_v}}.$$

From the demand for raw capital (k_e) from the energy sector (eq. 23), we find the following ratio:

$$\zeta_2 \equiv \frac{k_e}{Y_e} = \frac{1}{X_e} \alpha_e \omega_{k_e} \frac{1}{r_{k_e}}.$$

Maximizing the profit function of energy firms in eq. (1) with respect to the composite of crude energy (V_e), we get the following condition:

$$\frac{1}{X_{e,t}} \frac{\alpha_e \left(1 - \omega_{k_e}\right) Y_{e,t}}{V_{e,t}} = p_{v,t}.$$

From this condition, it is possible to find the ratio between V_e and Y_e:

$$\zeta_3 \equiv \frac{V_e}{Y_e} = \frac{1}{X_e} \alpha_e \left(1 - \omega_{k_e}\right) \frac{1}{p_v}.$$

We then define the scaled level of production in the energy sector ($\hat{Y}_e$):

$$\hat{Y}_e \equiv Y_e a_{z_e}^{ss\,\frac{1}{\alpha_e - 1}} = n_e \left[\zeta_2^{\omega_{k_e}} \zeta_3^{1-\omega_{k_e}}\right]^{\frac{\alpha_e}{1-\alpha_e}}.$$

Using the resource constraint for $\mathcal{S}_c$ (eq. 17), and that, from eqs. (38, 39 and 40), $c_e = \frac{1-\omega_{cc}}{\omega_{cc}} c_c$, it follows that:

$$\frac{\omega_{cc}}{1 - \omega_{cc}} c_e = Y_c - \delta_{k_c} k_c - \delta_{k_e} k_e.$$

Using the resource constraint in S_e (eq. 18), the following condition holds:

$$\frac{\omega_{cc}}{1 - \omega_{cc}} \left(Y_e - m_e\right) = Y_c - \delta_{k_c} k_c - \delta_{k_e} k_e,$$

so that:

$$\frac{\omega_{cc}}{1 - \omega_{cc}} \left(a_{z_e}^{ss}\right)^{\frac{1}{1-\alpha_e}} \hat{Y}_e + \delta_{k_e} \zeta_2 \left(a_{z_e}^{ss}\right)^{\frac{1}{1-\alpha_e}} \hat{Y}_e = Y_c - \delta_{k_c} k_c + \frac{\omega_{cc}}{1 - \omega_{cc}} m_e.$$

From which we find the normalizing constant $a_{z_e}^{ss}$:

$$a_{z_e}^{ss} = \left[\left(Y_c - \delta_{k_c} k_c + \frac{\omega_{cc}}{1 - \omega_{cc}} m_e\right) \left(\frac{\omega_{cc}}{1 - \omega_{cc}} \hat{Y}_e + \delta_{k_e} \zeta_2 \hat{Y}_e\right)^{-1}\right]^{1-\alpha_e}.$$

This allows us to find the steady-state value of a_{z_e}, Y_e, k_e, V_e, c_e and c_c:

$$Y_e = a_{z_e}^{ss\,\frac{1}{1-\alpha_e}} \hat{Y}_e,$$

$$k_e = \zeta_2 Y_e, \qquad V_e = \zeta_3 Y_e,$$

$$c_e = Y_e - m_e, \qquad c_c = \frac{\omega_{cc}}{1-\omega_{cc}} c_e.$$

From the demand for oil, gas and coal by the energy sector eqs. (24, 25 and 26), we obtain the following ratios:

$$\zeta_5 \equiv \frac{V_o}{V_e} = \left[\frac{p_o}{\alpha_e (1-\omega_{k_e}) \frac{1}{X_e} Y_e \frac{1}{V_e} a_{V_o} \omega_o^{\frac{1}{\sigma_v}}} \right]^{-\sigma_v},$$

$$\zeta_6 \equiv \frac{V_g}{V_e} = \left[\frac{p_g}{\alpha_e (1-\omega_{k_e}) \frac{1}{X_e} Y_e \frac{1}{V_e} a_{V_g} \omega_g^{\frac{1}{\sigma_v}}} \right]^{-\sigma_v},$$

$$\zeta_7 \equiv \frac{V_c}{V_e} = \left[\frac{p_c}{\alpha_e (1-\omega_{k_e}) \frac{1}{X_e} Y_e \frac{1}{V_e} a_{V_c} (1-\omega_o-\omega_g)^{\frac{1}{\sigma_v}}} \right]^{-\sigma_v}.$$

So that V_o, V_g and V_c are equal to the following expressions:

$$V_o = \zeta_5 V_e, \qquad V_g = \zeta_6 V_e, \qquad V_c = \zeta_7 V_e.$$

The composite of consumption ($\bar{c}$) is given by the following equation:

$$\bar{c} = \left(\omega_{c_c}^{\frac{1}{\sigma_c}} c_c^{\frac{\sigma_c-1}{\sigma_c}} + (1-\omega_{c_c})^{\frac{1}{\sigma_c}} c_e^{\frac{\sigma_c-1}{\sigma_c}} \right)^{\frac{\sigma_c}{\sigma_c-1}}.$$

From which the marginal utilities of consumption are obtained:

$$u_{c_c} = \omega_{cc}^{\frac{1}{\sigma_{cc}}} \frac{1}{\bar{c}} \left(\frac{\bar{c}}{c_c} \right)^{\frac{1}{\sigma_{cc}}}, \qquad u_{c_e} = (1-\omega_{cc})^{\frac{1}{\sigma_{cc}}} \frac{1}{\bar{c}} \left(\frac{\bar{c}}{c_e} \right)^{\frac{1}{\sigma_{cc}}}.$$

From the labor demand conditions, eqs. (22 and 29), the wage rates in the two sectors are found:

$$w_e = (1-\alpha_e) Y_e \frac{1}{X_e} \frac{1}{n_e}, \qquad w_c = (1-\alpha_c) Y_c \frac{1}{X_c} \frac{1}{n_c}.$$

This allows us to pin down the steady-state values for the labor disutility parameters φ^e and φ^c:

$$\varphi^e = p_e w_e u_{c_c} \frac{1}{X_{w_e}} \frac{1}{{n_e}^{\nu_e}}, \qquad \varphi^c = w_c u_{c_c} \frac{1}{X_{w_c}} \frac{1}{{n_c}^{\nu_c}}.$$

Finally, profits of retailers and unions in steady state are given by:

$$\Pi_{r_e} = \left(1 - \frac{1}{X_e}\right) Y_e, \quad \Pi_{r_c} = \left(1 - \frac{1}{X_c}\right) Y_c,$$

$$\Pi_{u_e} = \left(1 - \frac{1}{X_{w_e}}\right) w_e n_e, \quad \Pi_{u_c} = \left(1 - \frac{1}{X_{w_c}}\right) w_c n_c.$$

Regarding the crude energy block, we impose that:

$$\log(p_f) = \log(p_f^{ss}).$$

By the equations of the SVAR model (eq. 7), this implies that:

$$\Delta \log(GDP)^{\mathrm{W}} = \left[\frac{1}{1 - a_{1,11} - a_{2,11}}\right] \left[c_W + (a_{1,12} + a_{2,12}) \log(p_f)\right].$$

We define for convenience ζ_8 and ζ_9 as:

$$\zeta_8 \equiv (a_{0,21} - a_{1,21} - a_{2,21}) \left[c_W + (a_{1,12} + a_{2,12}) \log(p_f)\right] \frac{1}{(1 - a_{1,11} - a_{2,11})},$$

$$\zeta_9 \equiv (a_{1,22} + a_{2,22} - 1) \log(p_f).$$

The constant c_{p_f} is then pinned down by the following condition:

$$c_{p_f} = \zeta_8 - \zeta_9.$$

Finally, the loading λ_o, λ_g and λ_c must be equal to the following expressions to meet the targets:

$$\lambda_o = \frac{p_o^{ss}}{p_f^{ss}}, \qquad \lambda_g = \frac{p_g^{ss}}{p_f^{ss}}, \qquad \text{and} \qquad \lambda_c = \frac{p_c^{ss}}{p_f^{ss}},$$

and the idiosyncratic terms are equal to their unconditional mean:

$$a_{p_o} = 0, \qquad a_{p_g} = 0, \qquad \text{and} \qquad a_{p_c} = 0.$$

C Data Construction

Gross Domestic Product

Real gross domestic product (GDP) in the euro area from 1990:Q1 to 1995:Q1 is retrieved from the Gross Domestic Product series (YER code) in the Area-Wide Model (AWM) database constructed by Fagan et al. (2005), and after 1995:Q1 by Eurostat (CLVMEURSCAB1GQEA19 series). The series is seasonally adjusted and measured in millions of chained 2010 euros. We divide it by the total population of the euro area (provided by the World Bank and retrieved from the SPPOPTOTLEMU series by FRED) to transform it into per capita terms. The series is taken in log differences and demeaned.

Consumption

Consumption in the euro area from 1990:Q1 to 1995:Q1 is retrieved from the Individual Consumption Expenditure (PCR series) in the AWM database, and afterwards by Eurostat (NAEXKP02EZQ189S series). The series is seasonally adjusted and measured in millions of chained 2012 euros. We divide it by the total population of the euro area (SPPOPTOTLEMU) to transform it into per capita terms. The series is taken in log differences and demeaned.

Investment

Investment in the euro area from 1990:Q1 to 1995:Q1 is obtained as the Gross Fixed Capital Formation (ITR series) in the AWM database, and after by Eurostat (NAEXKP04E Q652S series, retrieved from FRED). The series is seasonally adjusted and measured in millions of chained 2012 euros. We divide it by the total population of the euro area (SPPOPTOTLEMU) to transform it into per capita terms. The series is taken in log differences and demeaned.

Employment

Employment in the euro area from 1990:Q1 to 1995:Q1 is retrieved from the Total Employment (LNN series) in the AWM database, and after by Eurostat (NAMQ_10_PE table). The series is seasonally adjusted and measured in thousands of persons. We divide it by the total population of the euro area (SPPOPTOTLEMU) to transform it into per capita terms. The series is taken in log differences.

Inflation

Inflation in the euro area from 1990:Q1 to 1995:Q1 is retrieved from the GDP Deflator (YED series) in the AWM database, and afterward by Eurostat (namq_10_gdp_1 table). The series is taken in log differences to transform the deflator into an inflation rate.

Energy inflation

Energy inflation in the euro area from 1990:Q1 to 1995:Q1 is retrieved from the HICP Energy (HEGSYA series) in the AWM database, and after by OCSE (ENRGY0EZ19M0 86NEST series, retrieved from FRED). The series is a seasonally and calendar-adjusted index. We take log differences to get inflation rates.

Oil price inflation

Oil price is obtained from the Spot Crude Oil Price for West Texas Intermediate provided by the Federal Reserve Bank of St. Louis (WTISPLC series, retrieved from FRED), as a measure of the global price. The series is measured in dollars, so we convert it into euros by multiplying it by the euro/dollar exchange rate (the EXR series in the AWN database before 1995:Q1 and afterward the DEXUSEU series provided by the Board of Governors of the Federal Reserve System). We finally take log differences to have inflation rates.

Natural gas price inflation

The price of natural gas in the European Union is obtained from the International Monetary Fund (PNGASEUUSDM series, retrieved from FRED). We convert the series in euros in the same way as for the oil price and then take log differences to get inflation rates.

Coal price inflation

The global price of coal is obtained as the Global price of Coal, Australia, provided by the International Monetary Fund (PCOALAUUSDQ series, retrieved from FRED). This series is the representative price on the global market and is determined by the largest exporter of this commodity, see `https://www.imf.org/en/Research/commodity-prices`. In the same way as above, we convert the series in euros and then take log differences to obtain inflation rates.

Nominal wage inflation

To construct data on nominal wage inflation in the euro area, we divide the data on total compensation by total employment. Until 1995:Q1 total employment is taken from the AWM database (LNN series), and afterward from Eurostat (namq_10_pe table). These series are measured in thousands of persons and are seasonally adjusted. We obtain compensation as the Compensation of Employees series from the AWN database (WIN series) and Eurostat (namq_10_gdp table). These series are measured in millions of euros and are seasonally and calendar adjusted. We take log differences to get wage inflation rates.

Oil, natural gas and coal quantities

We obtain data on quantities of oil, coal and gas from Eurostat's Gross Available Energy data provided in the Simplified Energy Balances (nrg_oil, nrg_gas and nrg_coal series). As stated by Eurostat:[24]

"*Gross available energy means the overall supply of energy for all activities on the territory of the country. [...] Gross available energy for the total of all products (fuels) is the most important aggregate in energy balances and represents the quantity of energy necessary to satisfy all the energy demands.*"

These series are measured in tons of oil equivalent (toe). We divide them by the total population of the euro area (SPPOPTOTLEMU series) to transform them into per capita terms and finally take log differences to get growth rates.

Interest rate

We obtain data on the nominal short-term interest rate as the Euribor 3-month. Before 1995:Q1 we get the data from the AWM database (STN series) and Eurostat (irt_st_q table).

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[24] `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Gross_available_energy`.

Global GDP

The series of global GDP is obtained as the quarterly GDP of OECD countries, retrieved from OECD (VPVOBARSA series). The series is seasonally adjusted and expressed taking into account purchasing power parity. We take log differences to get growth rates.

D SVAR Estimation

As stated in the main text, the growth rate of global GDP, $\Delta \log \left(GDP_t^{\mathrm{W}}\right)$, and the log of common factor of oil coal and gas, $\log\left(p_{f,t}\right)$, are determined according to the following bivariate SVAR model:

$$\boldsymbol{A}_0 \begin{bmatrix} \Delta \log \left(GDP_t^{\mathrm{W}}\right) \\ \log\left(p_{f,t}\right) \end{bmatrix} = \boldsymbol{c} + \sum_{j=1}^{2} \boldsymbol{A}_j \begin{bmatrix} \Delta \log \left(GDP_{t-j}^{\mathrm{W}}\right) \\ \log\left(p_{f,t-j}\right) \end{bmatrix} + \begin{bmatrix} \varepsilon_{W,t} \\ \varepsilon_{p_f,t} \end{bmatrix}. \tag{45}$$

The coefficient matrices in eq. (45) are given by:

$$\boldsymbol{A}_0 \equiv \begin{bmatrix} 1 & 0 \\ a_{0,21} & 1 \end{bmatrix}, \boldsymbol{c} \equiv \begin{bmatrix} c_W \\ c_{p_f} \end{bmatrix}, \boldsymbol{A}_1 \equiv \begin{bmatrix} a_{1,11} & a_{1,12} \\ a_{1,21} & a_{1,22} \end{bmatrix} \text{ and } \boldsymbol{A}_2 \equiv \begin{bmatrix} a_{2,11} & a_{2,12} \\ a_{2,21} & a_{2,22} \end{bmatrix}. \tag{46}$$

The SVAR parameters in equation (46) are estimated together with the other parameters using the RWMH algorithm; their prior and posterior are reported in the following table:

Table 4: Estimation results. The table shows the SVAR parameters. The table reports the parameter's symbol (Symbol), the prior shape (Prior), prior mean and standard deviation (Mean, St. Dev), and the posterior mean (Post. Mean) and standard deviation (Post. St. Dev). $\mathcal{N}$ *is the Normal distribution.*

SVAR parameters				
Symbol	Prior	Mean, St. Dev.	Post. Mean	Post. St. Dev
$100 \times c_W$	$\mathcal{N}$	(0.14, 0.03)	0.17	0.03
$a_{0,21}$	$\mathcal{N}$	(-0.18, 0.04)	-0.18	0.03
$a_{1,11}$	$\mathcal{N}$	(0.76, 0.15)	0.66	0.06
$a_{1,12}$	$\mathcal{N}$	(0.02, 0.00)	0.01	0.00
$a_{1,21}$	$\mathcal{N}$	(-0.41, 0.08)	-0.38	0.08
$a_{1,22}$	$\mathcal{N}$	(0.98, 0.20)	0.98	0.04
$a_{2,11}$	$\mathcal{N}$	(-0.16, 0.03)	-0.17	0.03
$a_{2,12}$	$\mathcal{N}$	(-0.02, 0.00)	-0.01	0.00
$a_{2,21}$	$\mathcal{N}$	(-0.10, 0.02)	-0.10	0.02
$a_{2,22}$	$\mathcal{N}$	(-0.14, 0.03)	-0.22	0.03

References

Fagan, G., Henry, J., and Mestre, R. (2005). An Area-Wide Model for the Euro Area. *Economic Modelling*, 22(1):39–59.

Online Appendix - Not for Publication - for “Energy Shocks, Pandemics and the Macroeconomy”

Luisa Corrado, Stefano Grassi, Aldo Paolillo and Francesco Ravazzolo.

E Additional Results

IRFs

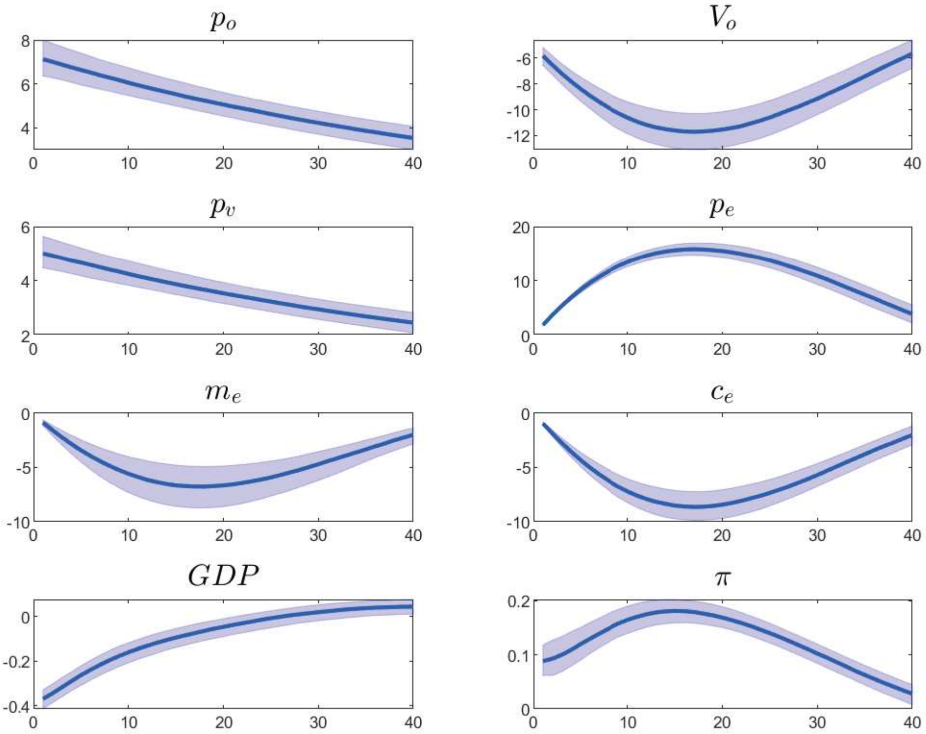


Figure 21: The IRFs of key model variables to an oil price shock.
Note: The shaded areas represent credible bands related to parameter uncertainty between the 20th and 80th percentiles. The IRFs represent percentage deviations from the steady state.

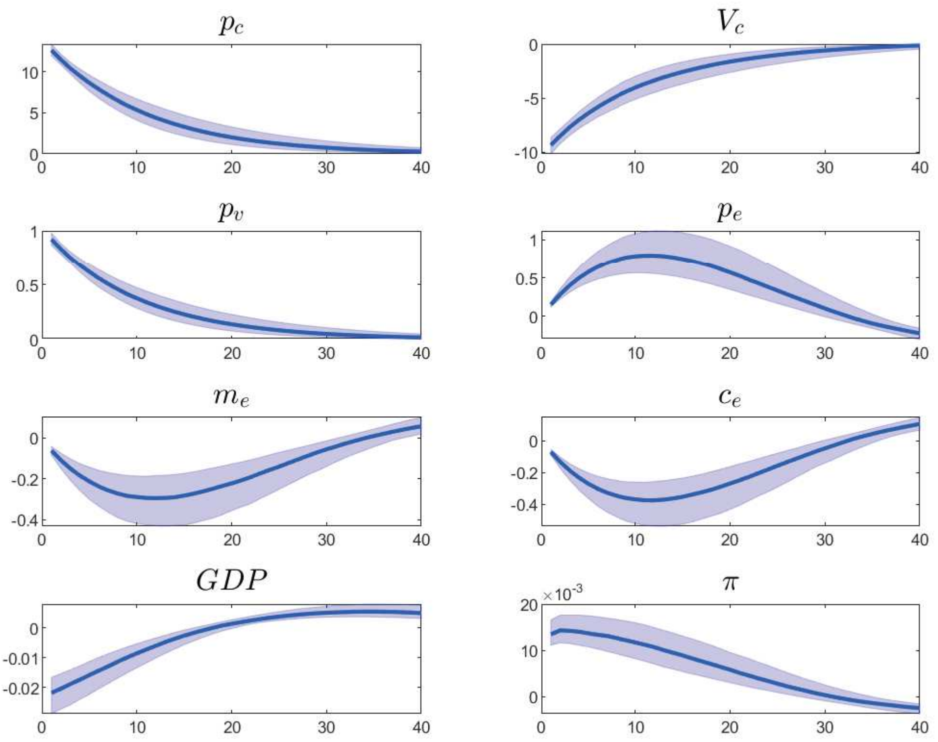


Figure 22: The IRFs of key model variables to a coal price shock.
Note: The shaded areas represent credible bands related to parameter uncertainty between the 20th and 80th percentiles. The IRFs represent percentage deviations from the steady state.

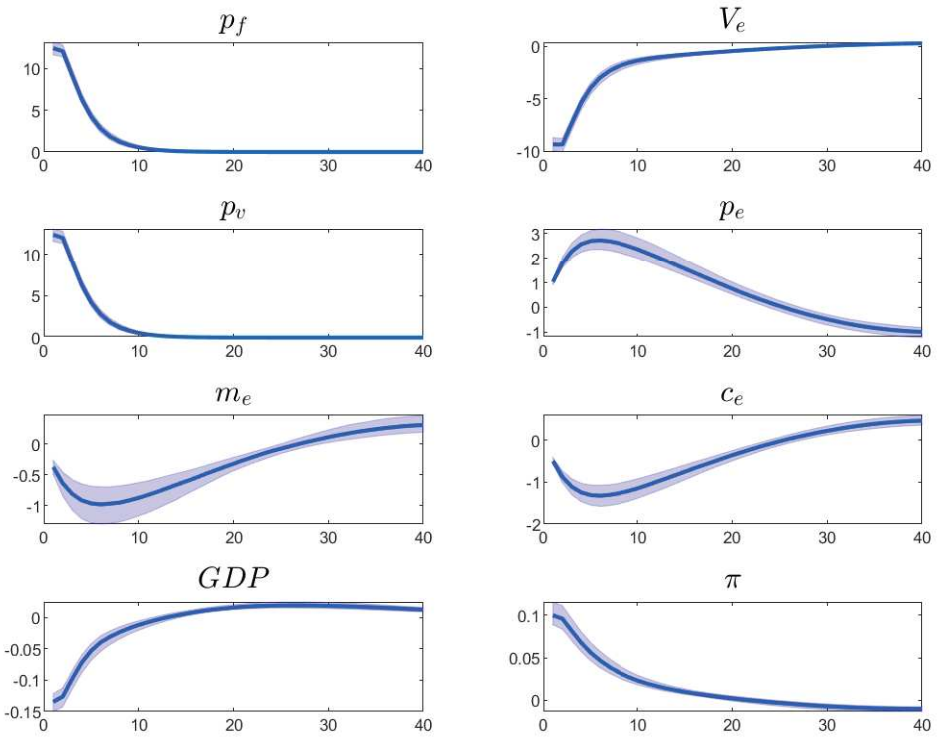
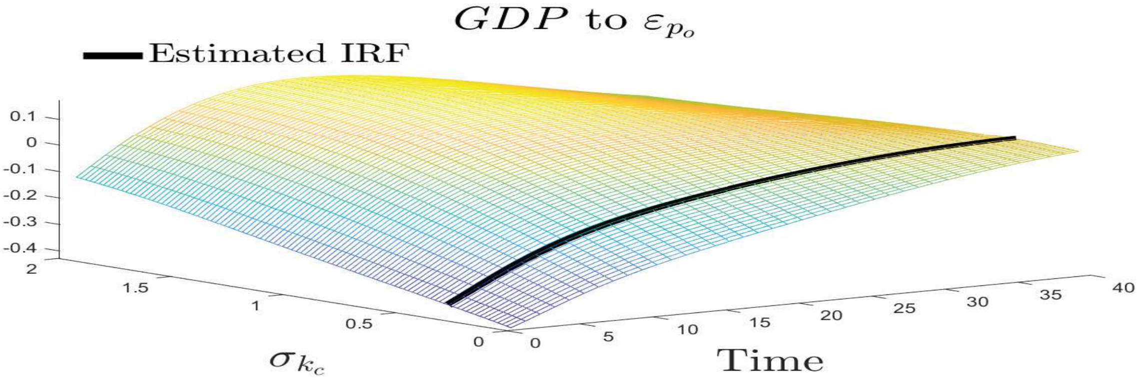
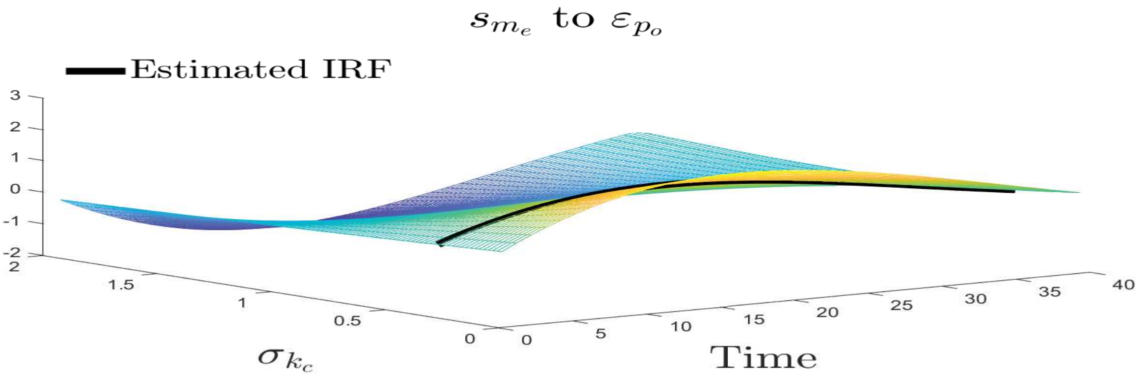


Figure 23: The IRFs of key model variables to a shock to the common factor of crude energy.
Note: The shaded areas represent credible bands related to parameter uncertainty between the 20th and 80th percentiles. The IRFs represent percentage deviations from the steady state.

The role of complementarities

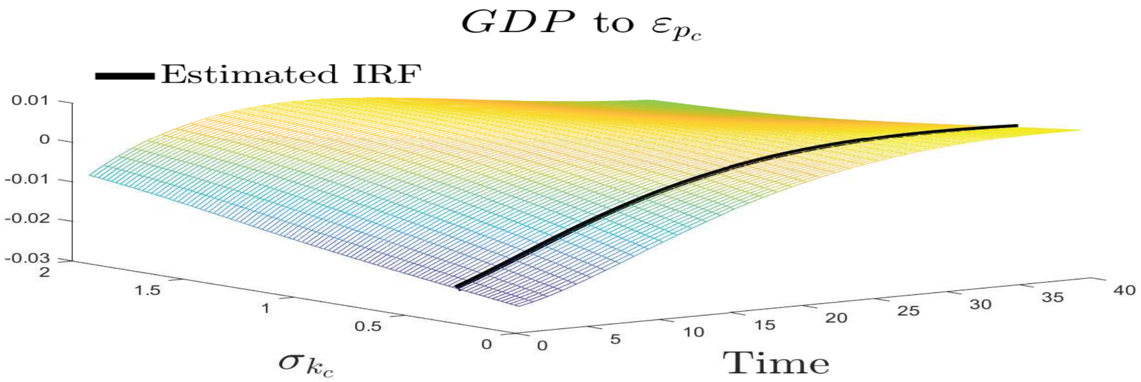


(a) IRF of GDP

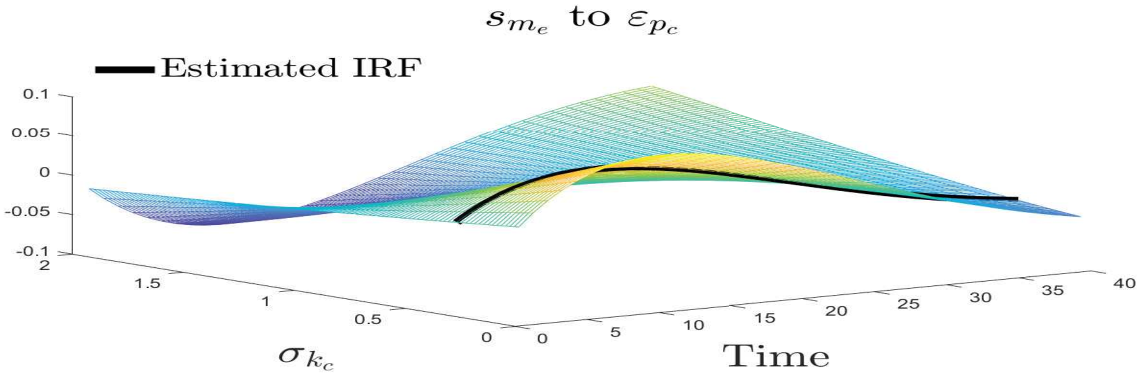


(b) IRF of s_{m_e}

Figure 24: The impact of the elasticity of substitution in production on the transmission of oil price shocks. Note: The plots represent the IRFs to a positive one standard deviation shock (ε_{p_o}) to the price of oil (p_o), computed at different values of the elasticity of substitution parameter σ_{k_c}. The black line represents the IRF at the estimated value of σ_{k_c}. The IRFs represent percentage deviations from the steady state for GDP and deviations from the steady state for s_{m_e}.

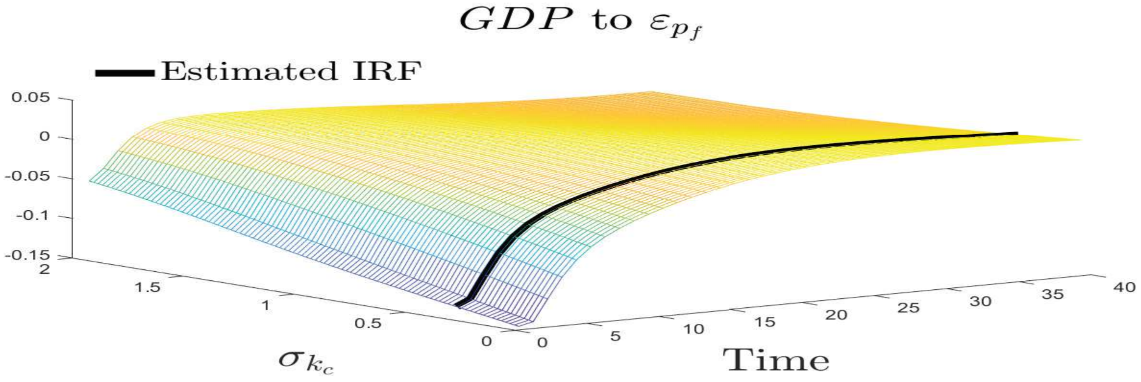


(a) IRF of GDP

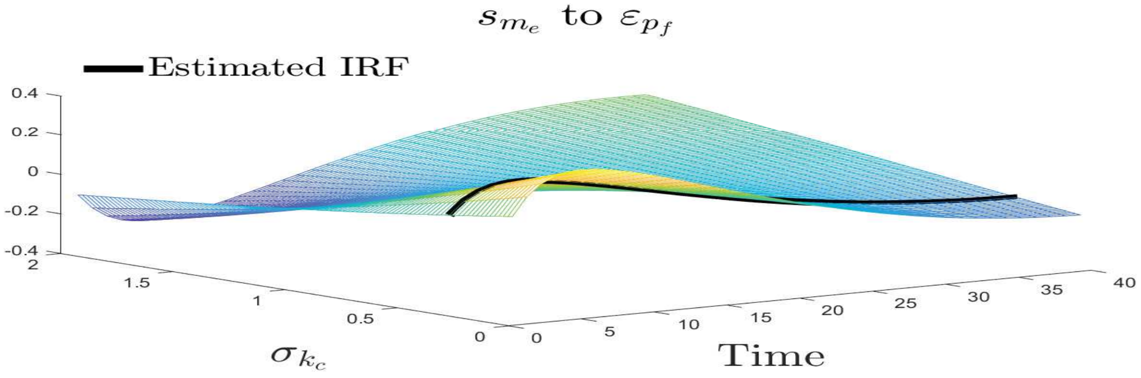


(b) IRF of s_{m_e}

Figure 25: The impact of the elasticity of substitution in production on the transmission of coal price shocks.
Note: The plots represent the IRFs to a positive one standard deviation shock (ε_{p_c}) to the price of coal (p_c), computed at different values of the elasticity of substitution parameter σ_{k_c}. The black line represents the IRF at the estimated value of σ_{k_c}. The IRFs represent percentage deviations from the steady state for GDP and deviations from the steady state for s_{m_e}.



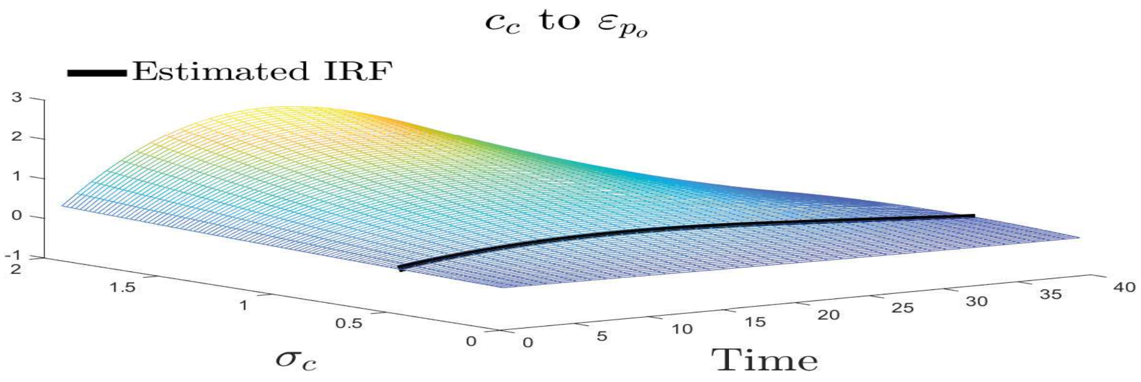
(a) IRF of GDP



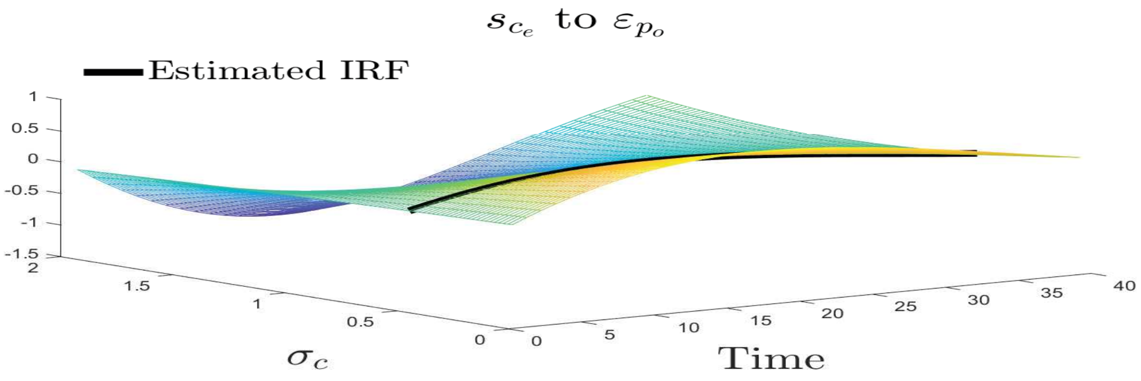
(b) IRF of s_{m_e}

Figure 26: The impact of the elasticity of substitution in production on the transmission of shocks to the common factor of crude energy.

Note: The plots represent the IRFs to a positive one standard deviation shock (ε_{p_f}) to the common factor of crude energy prices (p_f), computed at different values of the elasticity of substitution parameter σ_{k_c}. The black line represents the IRF at the estimated value of σ_{k_c}. The IRFs represent percentage deviations from the steady state for GDP and deviations from the steady state for s_{m_e}.



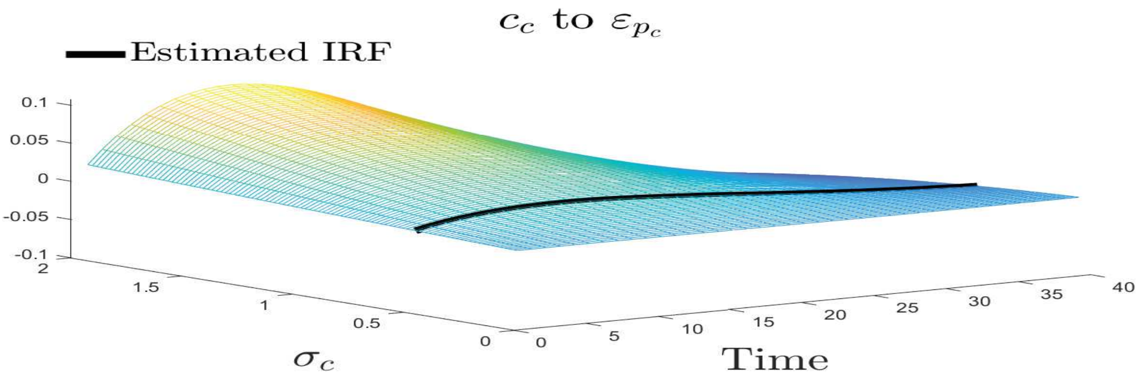
(a) IRF of GDP



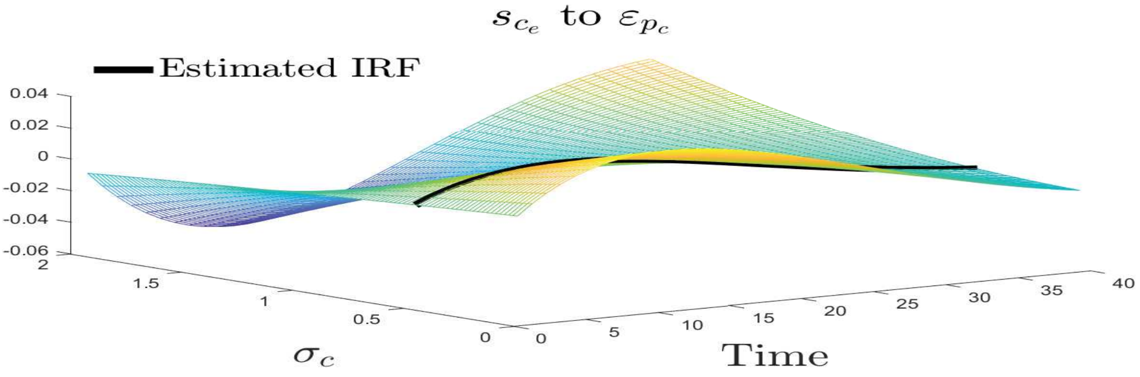
(b) IRF of s_{c_e}

Figure 27: The impact of the elasticity of substitution in consumption on the transmission of oil price shocks.

Note: The plots represent the IRFs to a positive one standard deviation shock (ε_{p_o}) to the price of oil (p_o), computed at different values of the elasticity of substitution parameter σ_c. The black line represents the IRF at the estimated value of σ_c. The IRFs represent percentage deviations from the steady state for c_c and deviations from the steady state for s_{c_e}.



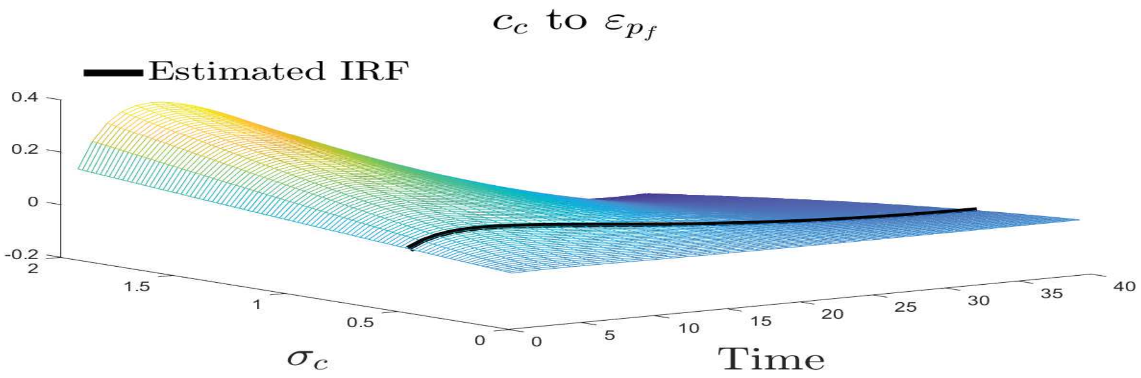
(a) IRF of GDP



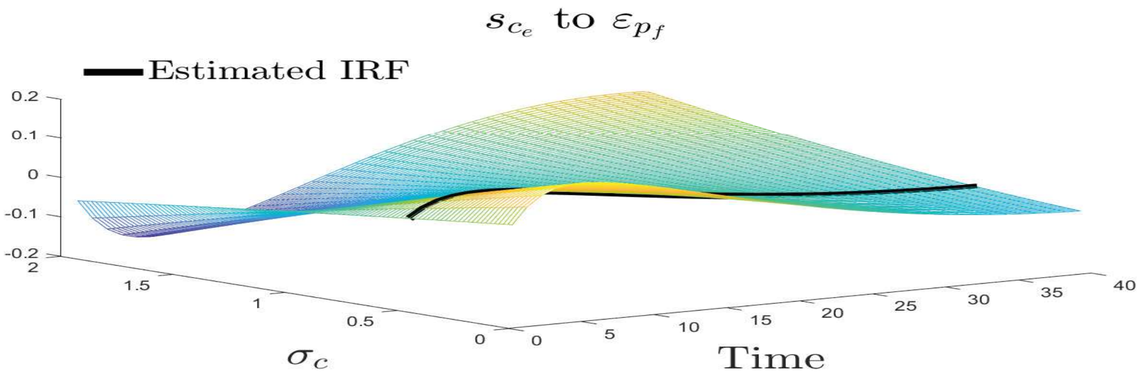
(b) IRF of s_{c_e}

Figure 28: The impact of the elasticity of substitution in consumption on the transmission of coal price shocks.

Note: The plots represent the IRFs to a positive one standard deviation shock (ε_{p_c}) to the price of coal (p_c), computed at different values of the elasticity of substitution parameter σ_c. The black line represents the IRF at the estimated value of σ_c. The IRFs represent percentage deviations from the steady state for c_c and deviations from the steady state for s_{c_e}.



(a) IRF of GDP



(b) IRF of s_{c_e}

Figure 29: The impact of the elasticity of substitution in consumption on the transmission of shocks to the common factor of crude energy.
Note: The plots represent the IRFs to a positive one standard deviation shock (ε_{p_c}) to the common factor of crude energy (p_f), computed at different values of the elasticity of substitution parameter σ_c. The black line represents the IRF at the estimated value of σ_c. The IRFs represent percentage deviations from the steady state for c_c and deviations from the steady state for s_{c_e}.

The role of wage indexation

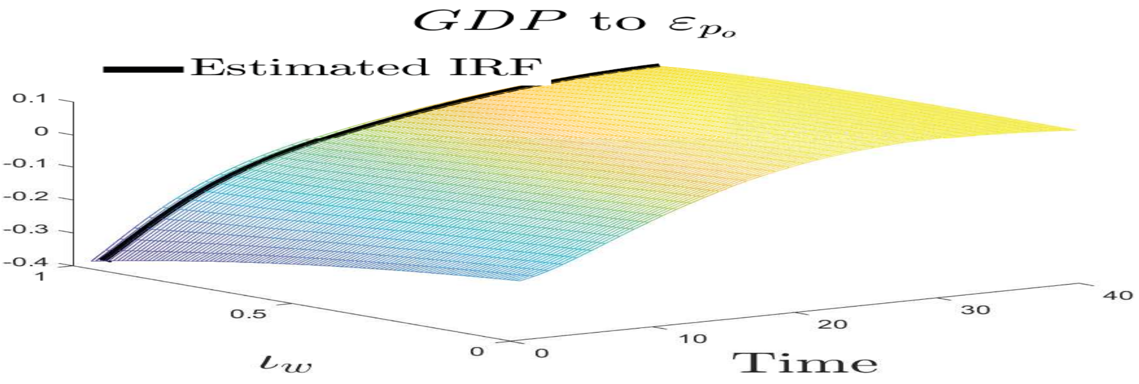


Figure 30: *The role of wage indexation on the transmission of gas price shocks. The plots represent the IRFs of GDP to a positive one standard deviation oil price shock* (ε_{p_g})*, depending on the degree of wage indexation* (ι_w)*. The black line represents the IRF at the estimated value of* ι_w*. The IRFs represent percentage deviations from the steady state.*

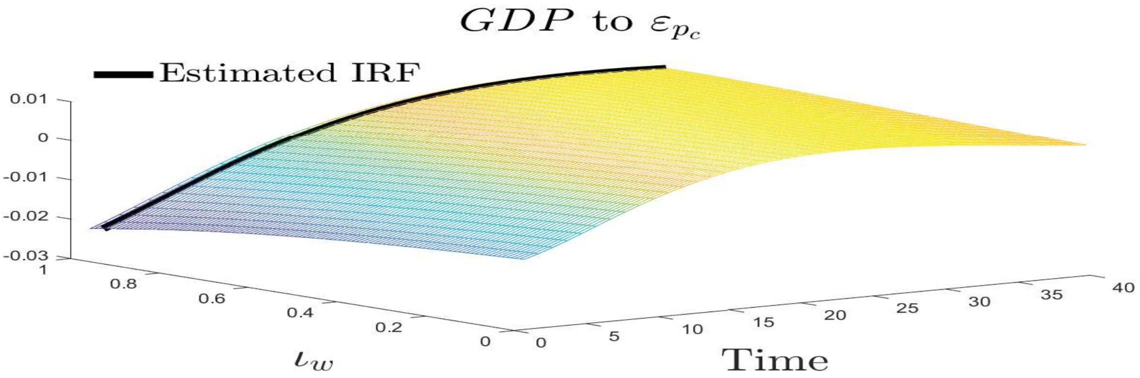


Figure 31: *The role of wage indexation on the transmission of gas price shocks. The plots represent the IRFs of GDP to a positive one standard deviation coal price shock* (ε_{p_c})*, depending on the degree of wage indexation* (ι_w)*. The black line represents the IRF at the estimated value of* ι_w*. The IRFs represent percentage deviations from the steady state.*

Monetary Policy

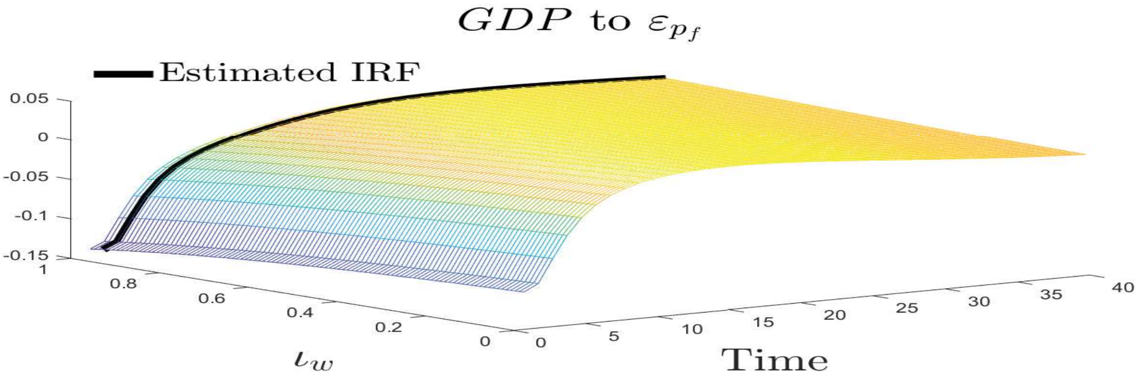
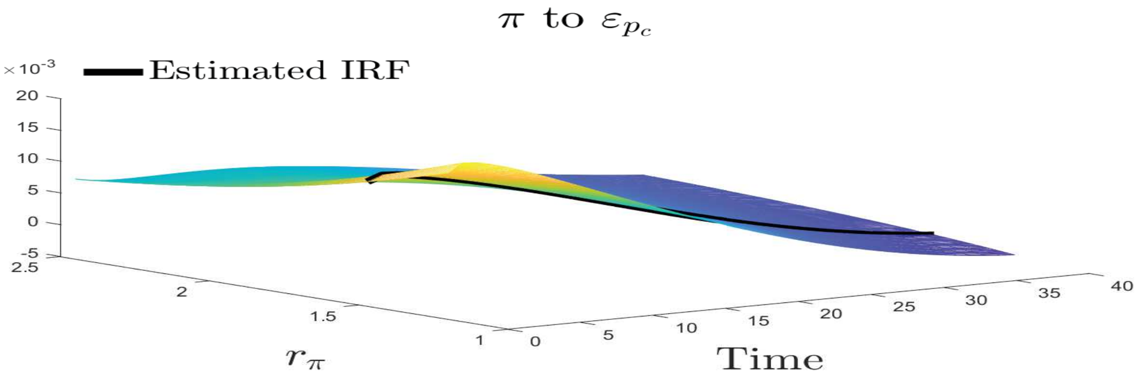
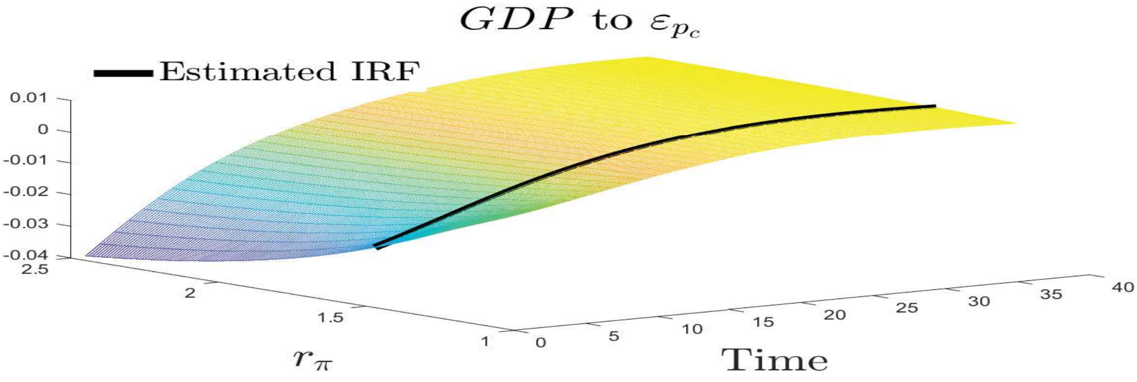


Figure 32: The role of wage indexation on the transmission of gas price shocks. The plots represent the IRFs of GDP to a positive one standard deviation shock to the common factor of crude energy (ε_{p_f}), depending on the degree of wage indexation (ι_w). The black line represents the IRF at the estimated value of ι_w. The IRFs represent percentage deviations from the steady state.

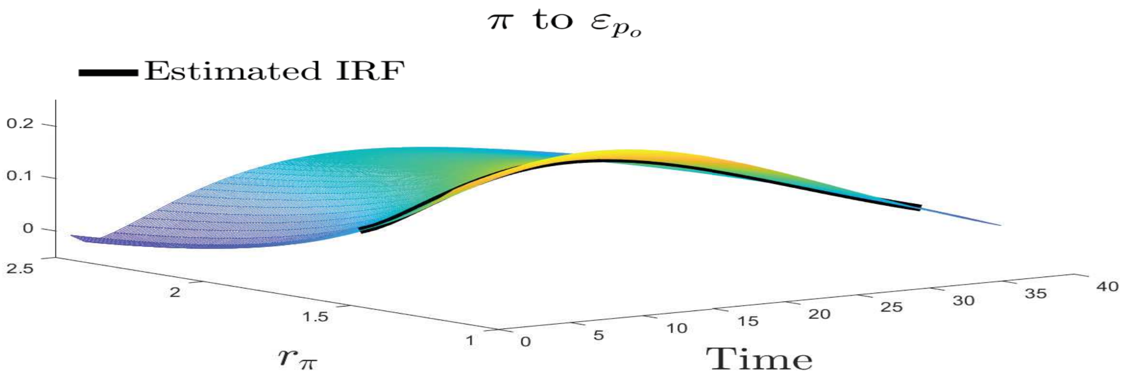


(a) Inflation

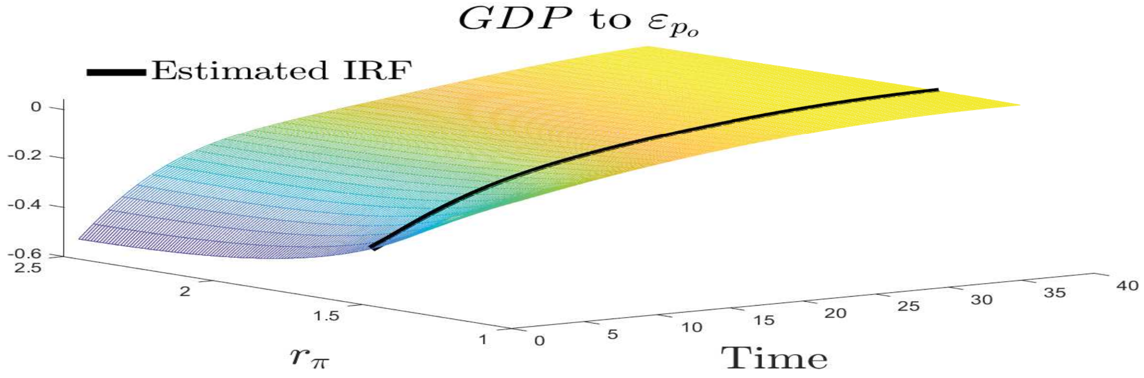


(b) GDP

Figure 33: The impact of monetary policy on the IRFs.
Note: The plots represent the IRFs of inflation and GDP to a positive one standard deviation shock to the price of coal (ε_{p_c}), varying the degree of responsiveness to inflation by the central bank (r_π). The IRFs represent percentage deviations from the steady state.

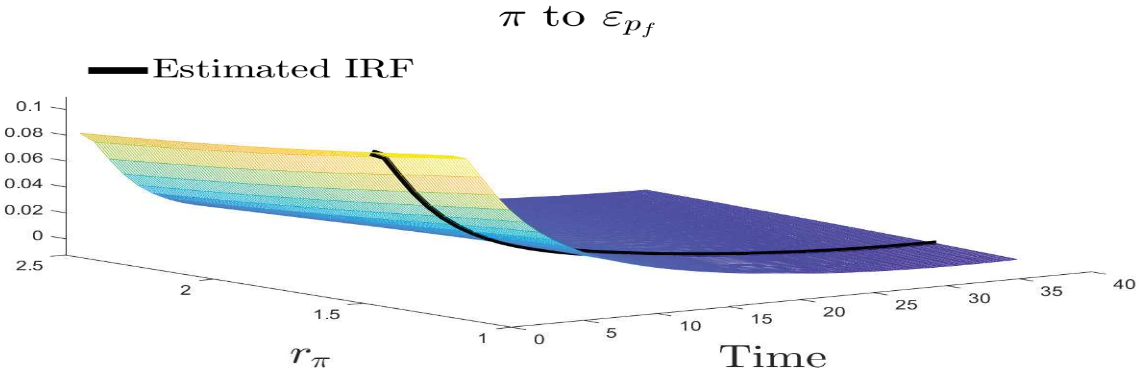


(a) Inflation

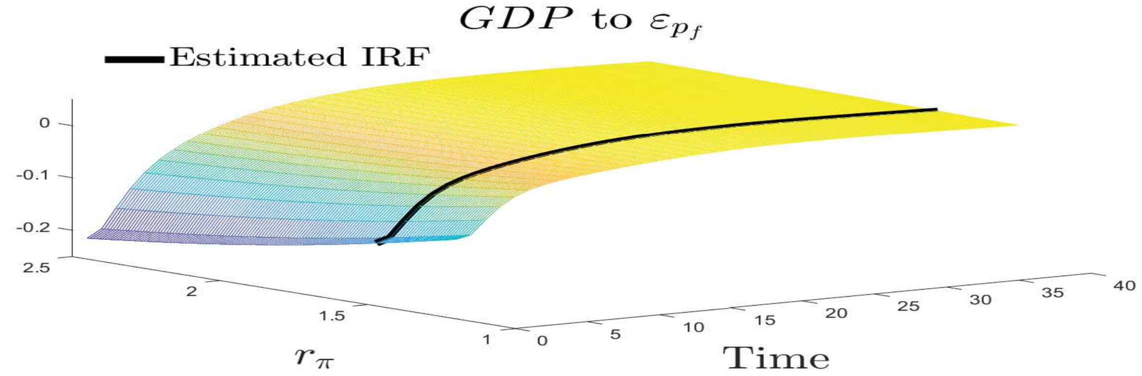


(b) GDP

Figure 34: The impact of monetary policy on the IRFs.
Note: The plots represent the IRFs of inflation and GDP to a positive one standard deviation shock to the price of oil (ε_{p_o}), varying on the degree of responsiveness to inflation by the central bank (r_π). The IRFs represent percentage deviations from the steady state.



(a) Inflation



(b) GDP

Figure 35: The impact of monetary policy on the IRFs.
Note: The plots represent the IRFs of inflation and GDP to a positive one standard deviation shock to the common factor of crude energy prices (ε_{p_f}), varying on the degree of responsiveness to inflation by the central bank (r_π). The IRFs represent percentage deviations from the steady state.

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