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Summary

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Keywords: Energy shocks; Policy analysis; Agent-based models; Macroeconomic dynamics

JEL Classification: C63, E63, O13, Q43

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Energy price shocks and stabilization policies in a multi-agent macroeconomic model for the Euro Area*

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Abstract

Soaring energy prices since fall 2021 have prompted European governments to introduce policy measures to support households and businesses. In this paper, we employ the MATRIX model, a multi-sector and multi-agent macroeconomic model calibrated on the Euro Area, to analyze the economic and distributional effects of different types of macro-stabilization policies in response to energy price shocks. Simulation results show that, in the absence of stabilization policies, an increase in fossil fuel price would lead to a sharp growth in price inflation and a severe contraction in real GDP, followed by a slow but steady recovery. We find no significant effects of generalized tax cuts and household subsidies, while firm subsidies promote a faster recovery but at the expense of greater financial instability in the medium term due to the resulting market distortions. If timely adopted, government-funded energy tariff reduction is the most effective policy in mitigating GDP losses at relatively low public costs, especially if coupled with an extra-profit tax on energy firms. Energy entrepreneurs benefit from rising fuel prices in all policy scenarios, but to a lesser extent under energy tariff cuts and windfall profits tax, favouring, in that case, workers and downstream firms owners.

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1. Introduction

In the wake of the COVID-19 pandemic, the global economy has been shaken by another shock that risks undermining the efforts undertaken by public authorities to ensure a proper recovery – the energy crisis. Driven by turmoil in natural gas markets, fossil fuel prices started rising in the second half of 2021 and rapidly reflected in higher electricity prices for households and business around the world (Schnabel, 2022). The global energy crisis was triggered by several factors pertaining to both the demand and supply side of energy markets (Alvarez and Molnar, 2021) such as the extraordinary rapid post-COVID recovery; a cold and long 2021-22 winter in the Northern Hemisphere; a weaker-than-expected increase in energy supply due to several weather-related events (e.g., droughts in Brazil that curtailed hydropower output, low wind generation in Northern Europe); the decline in fossil fuel investment, partly due to increasingly stringent climate policies, without an adequate rise in clean energy supply, resulting in an increasing reliance on natural gas as an intermediate fuel; not least, relevant geopolitical strife, particularly the Russo-Ukraine war starting in February 2022 (Liadze et al., 2022; Kilian and Plante, 2022).

The European Area is sensitive to all these causations because of the severe impact of the pandemic, the historical reliance on energy imports and the development of ambitious climate packages such as the “Fit for 55”. As a result, European governments adopted several policy measures to shield households and firms from surging energy prices. These came in different forms, such as reduced energy taxes, retail price regulations, transfers to vulnerable groups and windfall profits taxes (see Table 1, source: Sgaravatti et al., 2021). The rationale for public intervention might even go beyond the containment of an economic downturn, counteracting, for example, unintended social consequences which risk undermining internal cohesion (Douenne and Fabre, 2022). Nonetheless, those policies could be costly, and their application might bring side effects to the rest of the economy. That is even more so in times of economic uncertainty, where it could be challenging to disentangle the policies’ transmission channels and predict potential effects on different sectors of the economy.

The aim of this paper is to evaluate the economic and distributional consequences of different types of macroeconomic stabilization policies in response to energy price shocks. We do this by employing an extended version of the MATRIX model described in Ciola et al. (2022b), that is a multi-sector multi-agent macroeconomic model with an endogenous energy sector. The MATRIX model features a corporate sector, including heterogeneous consumption, capital and energy firms with interlocked input demands; a banking sector with heterogeneous banks; an exogenous fossil fuel sector (e.g., oil or natural gas); and a public sector, composed of a government and a central bank. Accordingly, the model can account for the relationship between the real and financial side of the economy, as well as the role played by fiscal and monetary policies. Moreover, it can be used to investigate the effects of an energy crisis captured by means of an exogenous shift in the price or quantity of the fossil fuel employed by the energy sector[1]. Contrary to the standard general equilibrium models, the agent-based framework allows to analyse not only the short-run impacts of the energy shock, but also the second order effects resulting from decentralized market interactions, feedback loops and out-of-equilibrium dynamics. For this reason, we believe the MATRIX model is a suitable tool to analyse the complexity of energy shocks and related macro-stabilization policies.

In this paper we extend the original model along two main directions. First, we re-calibrate the model to represent the macroeconomic behaviour of the Euro Area, while the original version focus on the US economy. Second, we implement a variety of policy experiments taking inspiration from the actual policies introduced by European governments in response to the current energy crisis,

[1]For a systematic analysis of the economic and distributional effects of different types of energy price and quantity shocks within the MATRIX model, see Ciola et al. (2022b)

Table 1: *National policies to shield consumers from rising energy prices.*

Country/Policy	Reduced energy tax	Retail/Wholesale price regulation	Transfers to vulnerables	Business support	Windfall profits tax	Mandate to SOEs	Other
Austria	✓		✓	✓			
Belgium	✓	✓	✓				✓
Bulgaria		✓		✓	✓		
Croatia	✓		✓				
Cyprus	✓		✓			✓	
Czech Republic	✓	✓	✓				
Denmark			✓				
Estonia	✓	✓	✓	✓			
Finland	✓		✓	✓			
France	✓	✓	✓			✓	
Germany	✓		✓				
Greece			✓	✓		✓	
Hungary	✓	✓					
Ireland	✓		✓				✓
Italy	✓		✓	✓	✓		
Latvia	✓		✓				
Lithuania		✓	✓				✓
Luxembourg			✓				
Netherlands	✓		✓				
Norway	✓		✓	✓			
Poland	✓	✓	✓				
Portugal	✓	✓	✓			✓	
Romania	✓	✓	✓		✓		
Slovenia	✓		✓	✓			
Spain	✓	✓✓	✓	✓	✓		
Sweden	✓		✓	✓			✓
United Kingdom		✓	✓	✓			

Source: Bruegel Datasets (Sgaravatti et al., 2022). Last update: 11 May 2022.

as presented in table 1. In particular, we consider five different policy scenarios: (i) generalized income tax reduction; (ii) household subsidy scheme; (iii) firm subsidy scheme (iv) extra-profit tax; (v) energy tariff reduction.

Simulation results show that, in the absence of stabilization policies, an energy price shock would lead to a sharp increase in price inflation and a lower real GDP, associated with spikes in firms' defaults and unemployment rate. We do not find significant effects of generalized tax cuts and consumer subsidy schemes, whereas firm subsidies can prompt a faster recovery, but at the expense of greater financial instability in the medium run due to the resulting market distortions. If timely adopted, government-funded energy tariff reduction is the most effective policy in mitigating GDP losses at relatively low public costs, especially if coupled with an extra-profit tax on energy firms. In terms of distributional impacts, we find that energy entrepreneurs benefit from a surge in fossil fuel price in all policy scenarios, but less so under energy tariff reduction and extra-profit tax, in favour of workers and downstream firms' owners.

The paper is structured as follows. Section 2 reviews the macroeconomic literature on energy shocks and related policy answers. Section 3 briefly describes the structure of the MATRIX model and the proposed extensions. Section 4 presents the design of policy experiments and discusses the simulation results. Lastly, Section 5 concludes by providing policy recommendations.

2. Literature review

The literature on energy shocks has blossomed in the aftermath of the oil crisis of the 1970s, mostly focusing on the nature of the shock and its macroeconomic implications. (Eastwood, 1992). It has been shown that energy price increases can cause a decline in output and employment (Bohi, 2017) and can be linked historically with recessions and inflation bursts (Kilian, 2008; Hamilton, 2008). Pindyck (1980) stresses that the channels through which higher energy prices affect the economy are essentially twofold: a direct cost channel, due to the role of energy as a productive input with limited substitution elasticities; an indirect cost channel, as the rise in energy prices eventually translates into higher general inflation, hence harming consumers' purchasing power. Nevertheless, their effects on the economy are puzzling because of the low share of energy in the production. This motivated researchers to identify alternative explanations, ranging from collusive practices in the related market to their relevance in the provision of capital sector services (Rotemberg and Woodford, 1996; Finn, 2000).

Some authors have stressed the importance of characterizing the nature of energy shocks in order to better understand the resulting macroeconomic consequences. For instance, oil price shocks could have different impacts depending on whether they are triggered by demand-side or supply-side factors (Blanchard and Gali, 2007; Herrera et al., 2019; Herrera and Rangaraju, 2019). van de Ven and Fouquet (2017) investigates the historical impacts of energy price shocks on UK GDP over the last 300 years, discovering that the impacts have changed over time depending on the nature of shocks and the type of energy source predominantly used. In particular, they find that the impacts of supply shocks rose with the increasing dependence on coal, and declined with the partial transition to oil. However, the transition from exporting coal to importing oil increased the negative impacts of demand shocks, suggesting that the system resilience to energy shocks has not improved with economic development. The transition to renewable sources, the integration of different national markets and the adoption of a well diversified energy mix are highly recommended policies aimed at improving an economy's vulnerability and resilience to shocks in the medium-long run.

Beyond these structural interventions in the energy market, some works have examined the role of timely fiscal and monetary policy measures to alleviate the short-run economic costs of higher energy prices for households and firms (Hickman et al., 1987), which is more in tune with the scope of this paper. The analysis of fiscal policy in response to energy shocks, like tax cuts or firms subsidies, largely overlaps with standard macroeconomic analysis of other shock types. Nonetheless, a peculiarity of this field is related to the so-called windfall or extra profits tax. Verbruggen (2008) highlights some uncertainty in the taxonomy regarding the windfall profits tax and proposes to separate the components related to rent skimming, monopoly or swindle profits from the actual unearned and unanticipated gains, the so-called "windfall profits". The latter has been recently studied in the context of developing countries in relation to sudden resource availability (Dagher et al., 2010) or emission trading schemes (Woerdman et al., 2009). Yet, the measure was originally conceived in the context of the US energy crisis of the 1970s (McIntyre, 1980), resulting in the Crude Oil Windfall Profit Tax Act of 1980 (Philip K. Verleger, 1980). The tax was in reality an excise tax and was eventually repelled in 1988 for different reasons: (i) a lower than expected tax revenues due to falling oil prices; (ii) administrative and compliance burden; (iii) a suspected negative effect on domestic oil production. Lazzari (2006) claims that a pure corporate income surtax on crude oil producers is more efficient than an excise tax as it allows to recoup any recent windfalls with less adverse economic effects. In terms of distributional impacts, Alexeev and Zakharov (2022) find that windfall profits had increased income inequality and benefited the wealthiest quantile of the population in regions with more intense rent-seeking. Also for this reason, in 2021 the European Commission advocated the proposal of transferring the proceeds from an excess profit tax on energy companies to the vulnerable groups in order to contain the negative economic and distributional effects of the energy crisis (Batlle et al., 2022).

Monetary policy is another relevant tool available to the policymaker to alleviate the economic impact of energy shocks (Bernanke et al., 1997; Binder, 2018). De et al. (2022) study the effects of three types of oil shocks on the US economy from 1978 to 2017, finding that monetary authorities tightened monetary policy to mitigate the inflationary pressure of unanticipated oil demand shocks. However, Pindyck (1980) states that the complete accommodation of the indirect costs might not always be the most optimal answer. Although the current crisis might not justify long-term inflation worries, a change in agent expectations of future prices could trigger a wage-price spiral that would inflict significant short-term economic pains (Kilian and Zhou, 2021). In this case, the policymaker should consider a prudent monetary policy to ensure price stability, but taking into account potential output losses. Indeed, as Bohi (2017) argues, the recessions following the oil shocks of the 1970s were rather due to the tightening of monetary policy than the oil shocks per se.

Fiscal policies, such as tax cuts and subsidies, seem to find a more relevant place in the 2021 energy crisis. Indeed, in response to the rise in natural gas and energy prices, most European governments struggle to operationalize sufficient alternative energy sources, bringing risks of supply disruptions (Alvarez and Molnar, 2021). More direct and faster measures (compared to energy efficiency investments) are then a viable solution to cope with short-run economic costs, as manifested by the list of national policies adopted by European countries described in table 1.

In the last decades, the economic effects of energy shocks and related stabilization policies have been object of study within the macroeconomic modelling literature as well, mainly through Dynamic Stochastic General Equilibrium (DSGE) and the Computable General Equilibrium (CGE) models.

Jacquinot et al. (2009) explore the links between oil prices and inflation by means of a DSGE model calibrated on the Euro area, finding that the strength of the link varies depending on the type of identified oil shock and the time horizon under consideration. Employing Bayesian methods with a DSGE model, Balke et al. (2010) finds that domestic shocks to productivity and preferences might amplify the effects of exogenous oil shocks: supply and demand shocks could have different impacts on GDP, but without the interaction with domestic factors, the effect of the shock could be very mild. Nakov and Pescatori (2010) find evidence that a reduced oil share on GDP contributed to the Great Moderation. Plante (2014) investigates the macroeconomic impacts of fuel subsidies in a small open economy model, finding that, regardless of how the subsidies are financed, they introduce market distortions and reduce aggregate welfare, both in net oil importing or exporting countries. Vásconez et al. (2015) analyse the stagflationary impact of oil price shocks with a NK-DSGE model, finding that increased energy efficiency attenuates the negative effect of an oil shock. Zhao et al. (2016) examines the impacts of different types of oil shocks in an open economy DSGE for China. They state that policies for controlling inflation should consider the global aspect of the shock, and diversify the energy sources. Huynh (2017) develops a New Keynesian model with an endogenous energy production to investigate the monetary policy answers to four types of price shocks, highlighting the role of structural rigidities in the shock transmission. Balke and Brown (2018) develop an estimated DSGE model for the US economy to evaluate how U.S. economic activity responds to oil price shocks, finding that the elasticity of GDP to oil price changes due to oil supply shocks.

Considering the CGE literature, Aydın and Acar (2011) study the impacts of oil shocks on the Turkish economy, finding a harmful reduction of consumption and income, but do not consider reactive policies targeted at consumers and firms, but rather a liberalization of the oil sector and investments in alternative energy sources. Doroodian and Boyd (2003) examines in a model of the US if an oil shock would pose inflation under different scenarios of technical progress, discovering a weak and diluting connection. Liu et al. (2015) develops a financial CGE for the Chinese economy and analyses monetary policy answers to oil shocks of different magnitudes, finding a trade-off between reserve ratio and interest rate policy on social stability.

As we have seen, the questions concerning energy shocks and related policy responses have been addressed by means of different methodologies, but mostly from an aggregate perspective, e.g. Pindyck (1980); Balke et al. (2010). However, the complex interrelation between the energy sector and the economy should be considered when evaluating the macroeconomic impact of energy price increases. This can be done in a micro-founded macroeconomic model with heterogeneous interacting agents capable of capturing out-of-equilibrium dynamics, distributional effects and feedback loops between different sectors. Moreover, the lack of timely data might prevent empirical assessment of short-terms impacts of stabilization policies in response to energy shocks. That would require a computational framework allowing to investigate the economic consequences of energy shocks and stabilization policies in different simulation scenarios. These considerations explain the growing interest in agent-based computational modelling as analytical tool to address energy topics (Hansen et al., 2019). By allowing for agent heterogeneity and decentralized interactions, agent-based models (ABM) bring new insights into the energy shock literature that the standard methodologies could be missing (Lengnick, 2013). For instance, the granularity and flexibility of agent-based framework allows to design highly detailed stabilization policies in response to energy shocks, taking also into account potential distributional effects on households and firms.

Policy analyses have been extensively explored in the macroeconomic ABM literature (Fagiolo and Roventini, 2012; Dawid and Delli Gatti, 2018), focusing on different policy areas such as fiscal (Dosi et al., 2013; Teglio et al., 2019), monetary (Delli Gatti and Desiderio, 2015; Giri et al., 2019), labor market (Dosi et al., 2018), macro-prudential (Aldasoro et al., 2017; Popoyan et al., 2017) and regional policies (Dawid et al., 2018) as well as virus containment interventions and vaccination strategies (Basurto et al., 2021; Delli Gatti et al., 2021). More recently, the potential of agent-based modelling for performing economic and policy analyses related to climate and energy issues has been increasingly recognized (Balint et al., 2017; Hansen et al., 2019; Castro et al., 2020). Works in this field have mainly focused on the economic impacts of climate shocks (Lamperti et al., 2018), the likelihood of energy transition and related economic risks (Hötte, 2020; Lamperti et al., 2020), the role of green fiscal, monetary and financial policies in the shift towards low-carbon economy (Ponta et al., 2018; Monasterolo and Raberto, 2018; Lamperti et al., 2021). Nonetheless, the questions concerning energy shocks and related stabilization policies have remained widely overlooked within the macroeconomic ABM literature. The only example is van der Hoog and Deissenberg (2011). Building on the EURACE@Unibi model (Deissenberg et al., 2008), this work investigates the economic effects of energy price shocks and the role of two automatic stabilizers in mitigating the negative effects, that is a consumer subsidy scheme and a tax reduction scheme. They find that rising energy prices result in a considerable reduction in GDP and investment. Stabilization policies help to accelerate the economic recovery, with tax reduction scheme yielding better outcomes both in the short and in the long run due to the positive impact on innovative investment and productivity. Instead, consumer subsidies have insignificant effects in short run and negatively affects the long-run dynamics since the lower investments by firms result in a structural loss of GDP.

Yet, the model used by van der Hoog and Deissenberg (2011) does not feature an explicit energy sector and, subsequently, the design of energy shocks is rather simplistic. The energy crisis is conceived as an exogenous increase in the production costs of capital goods firms, which is then transmitted to the final consumption good. Instead, our model is characterized by an endogenous energy sectors which is related via interlocked input demand to consumption and capital industries. This allows us to analyse the complex dynamics resulting from exogenous energy shocks hitting the economy, taking into consideration possible market imbalances, supply bottlenecks and feedback loops between the energy sector and the rest of the macroeconomy.

3. An overview of the model

The model depicts an economy composed of heterogeneous households, firms and banks, an exogenous fossil fuel sector, a central bank and a government. Households ($h = 1, \dots, \mathcal{n}^H$) are divided between workers ($\mathcal{n}^W$), entrepreneurs ($\mathcal{n}^F$) and bankers ($\mathcal{n}^B$). Firms ($f = 1, \dots, \mathcal{n}^F$) fall into three different sectors: energy services (E), consumption goods (C) and capital goods (K) sectors. The banking sector consists of ($b = 1, \dots, \mathcal{n}^B$) banks. Entrepreneurs and bankers own respectively one firm and bank each.

Households have different income sources depending on their type and economic status. They receive: a wage if they are an employed worker; a dividend if they are an entrepreneur or banker of an active company; a public transfer if their income falls short of a certain threshold. Households purchase a consumption good and accumulate savings in the form of bank deposits. In addition, firm and bank owners recapitalize their own company in case of default.

Firms purchase the required inputs in the respective market before starting the production, update their net worth based on profits or losses and, finally, adjust the desired price, quantity and related input demand for the subsequent period. Since firms pay for production factors in advance, if the expected cash outflow exceeds internal funds, they borrow from banks to cover the financing gap.

Banks hold households and firms' deposits, supply credit to firms in compliance with capital requirements and buy public bonds.

The government collects taxes on household and firms' income, distributes transfers to low-income individuals and bails out failed banks. If public spending exceeds tax revenues, the government finances the deficit by issuing new bonds, conditional on the fiscal space implied by the debt sustainability rule. The central bank sets the risk-free policy rate following an inertial Taylor rule.

Since the main focus of this work is the analysis of the macro-stabilization policies in response to energy shocks, in the next section we limit ourselves to briefly describe the overall macroeconomic environment of the model, including the sequence of the events, the behavioural rules followed by each agent group and the matching protocols governing the market transactions. For a more detailed description of the model, the interested reader is referred to the aforementioned original paper (Ciola et al., 2022b) or to the Appendix A of the present one.

3.1. Sequence of the events

In each simulation time period (t), the sequence of events unfolds as follows:

1. Initialization. At the beginning of each time step, firms are equipped with the amount of capital, debt and deposits inherited from the previous period. Further, they have already set their desired level of production, selling prices, and inputs demand.[2]

2. Markets for production factors:

   i. Labour market. Workers inelastically supply up to one unit of labour to hiring firms in exchange of a wage, pay income taxes and update their consumption budget;
   ii. Fossil fuel market. E-firms purchase the required energy input from the fossil fuel sector;
   iii. Energy market. E-firms generate energy services using fossil fuel, labour and capital stock and sell them to C- and K-firms.
   iv. Goods market. C-firms combine capital stock, labour and energy services to produce the consumption good and sell it to households;
   v. Capital good market. K-firms supply capital goods to C- and E-firms using labour and energy services. Capital goods are available from the subsequent period.

3. Profits, taxes and dividends. Once the respective market is closed, selling firms compute profits and pay taxes to the government, a share of their outstanding debt to banks, and dividends to the owners.

4. Firms default. If a firm is insolvent (negative net worth) or illiquid (negative liquidity), and the owner does not have sufficient resources to cover the losses, it declares default and the lending bank must account for non-performing loans. Subsequently, the owner initializes a new enterprise by purchasing the assets of the defaulted firm using his private wealth and, if not sufficient, a new bank credit.

5. Banks profits, NPL and default. Banks compute profits and pay taxes to the government and dividends to the owners. If non-performing loans result in a bank default, the bank compensates the losses by recurring to the banker's private wealth. If not sufficient, the government steps in to bail out the failed bank.

6. Planning price & quantity and input demand. Firms update their desired price-quantity strategy for the subsequent period and calculate conditional input demands accordingly. If the expected cost of inputs exceeds internal funds, firms resort to the credit market to cover the financing gap.

7. The government updates its fiscal position and adjusts the tax rate and social transfers to comply with a fiscal sustainability rule.

8. The central bank sets the policy rate following an inertial Taylor rule depending on the deviation from target inflation and unemployment.

[2] At the time $t = 0$, the system is initialized at the perfect competition steady state solution as shown in the Appendix A.6.

3.2. Households

Households $h = 1, \ldots, n^W$ can be either workers, entrepreneurs or bankers. [3] The nominal income of the households ($Y_{h,t}$) depends on their type:

$$Y_{h,t} = \begin{cases} W_t N_{w,t} & \text{for workers} \\ DIV_{f,t} - REC_{f,t} & \text{for entrepreneurs} \\ DIV_{b,t} - REC_{b,t} & \text{for bankers} \end{cases} \tag{1}$$

Workers inelastically supply $N_{w,t} \in (0,1)$ units of labour in exchange of an uniform salary, W_t, evolving over time according to institutional factors.[4] Entrepreneurs and bankers get dividends, $DIV_{h,t}$, if their company is economically active and sustain recapitalization costs, $REC_{h,t}$, if their company goes bankrupt. Moreover, low-income households receive a public transfer from the government if their income falls short of a given threshold. The household's consumption budget, $H^d_{h,t}$, is defined as the weighted sum between permanent income, $\bar{Y}_{h,t}$,[5] and financial wealth (i.e., deposits):

$$H^d_{h,t} = \bar{Y}_{h,t} + \chi D_{h,t}, \tag{2}$$

with χ being the propensity to consume out of financial wealth.

3.3. Firms

The corporate sector is composed of heterogeneous firms belonging to three different industries: energy, consumption and capital good.[6] Operating in a context of limited information and bounded rationality, firms determine the desired level of price and quantity according to a learning mechanism depending on evolving market conditions and strategic interaction. According to that, firms set the desired combination of price and quantity by imitating the $\{P, Q\}$ strategy of a target competitor[7], if more profitable, or by exploring a neighbour of their current strategy according to past excess demand. Formally, after identifying the target competitor s, the firm f updates its desired quantity and price for the subsequent period $\{Q^*_{f,t+1}, P_{f,t+1}\}$ as described below:

$$Q^*_{f,t+1} = \begin{cases} \zeta^Q Q^*_{f,t} + (1 - \zeta^Q) Q_{s,t} & \text{if } \Pi_{s,t} \geq \Pi_{f,t} \\ \zeta^Q Q^*_{f,t} + (1 - \zeta^Q) \hat{Q}_{f,t} & \text{otherwise} \end{cases} \tag{3}$$

$$P_{f,t+1} = \begin{cases} \zeta^P P_{f,t} + (1 - \zeta^P) P_{s,t} & \text{if } \Pi_{s,t} \geq \Pi_{f,t} \\ \zeta^P P_{f,t} + (1 - \zeta^P) \hat{P}_{f,t} & \text{otherwise} \end{cases} \tag{4}$$

where $P_{s,t}$, $Q_{s,t}$ and $\Pi_{s,t}$ are, respectively the price, quantity and profits of the target competitor s.

Equations (3) and (4) state that if the profits realized by the target firm s are higher than f's, price and desired quantity are smoothly adjusted towards the target's values, with ζ^Q and ζ^P being the speeds of adjustment. Otherwise, the firm f explores a neighbourhood its current strategy,

[3] See Appendix A.1 for a detailed description of the household sector.

[4] See Appendix A.2.

[5] The permanent income is defined as a weighted average of current net income and past permanent income levels, updated by expected inflation. The net income is the maximum between after-tax nominal income and social transfer received.

[6] See Appendix A.3 for a full description of the corporate sector.

[7] The choice of the target competitor is determined through a logit model decreasing with the technological distance. The latter is computed as the difference between firms' relative positions in the size distribution in terms of nominal production. In symbol, $d_{f,s,t} = \left| \hat{y}_{f,t} - \hat{y}_{s,t} \right|$, where $\hat{y}_{f,t} \equiv \frac{P_{f,t}Q_{f,t} - \min(P_{f,t}Q_{f,t})}{\max(P_{f,t}Q_{f,t}) - \min(P_{f,t}Q_{f,t})}$. In words, the probability for firm f of observing the target competitor s is higher the lower their distance, $d_{f,s,t}$.

$\{\hat{Q}_{f,t}, \hat{P}_{f,t}\}$ by drawing a random number from a uniform distribution, the sign of which being positive (negative) in case of excess demand (supply). This means that the direction of price and quantity adjustments is influenced by firm's past economic performance.

Given the desired production ($Q^*_{f,t+1}$) and expected input prices $\left\{\mathbb{E}_{f,t}\left[P_{j,t+1}\right]\right\}_{j=1}^{n}$, each firm f sets the conditional input demand that minimizes its expected direct costs $\mathbb{E}_{f,t}\left[DC_{f,t+1}\right]$ subject to a Constant Elasticity of Substitution (CES) production technology and irreversible investments, that is:

$$\min_{\{X_{f,j,t+1};\Delta X_{f,j,t+1}\}_{j=1}^{n}} \mathbb{E}_{f,t}\left[DC_{f,t+1}\right] = \sum_{j=1}^{n} \mathbb{E}_{f,t}\left[P_{j,t+1}\right] \Delta X_{j,f,t+1} \tag{5}$$

$$\text{s.t.} \quad Q^*_{f,t+1} = \left[\sum_{j=1}^{n} A_{j,f,t+1}\left(X_{j,f,t+1}\right)^{\rho_f}\right]^{\frac{1}{\rho_f}} \tag{6}$$

$$X_{j,f,t+1} = \Delta X_{j,f,t+1} + (1-\delta_j)X_{j,f,t} \tag{7}$$

$$\Delta X_{j,f,t+1} \geq 0 \text{ when } j \text{ indicates physical capital,} \tag{8}$$

where $\Delta X_{j,f,t+1}$, δ_j and $A_{j,f,t+1}$ are the additional input demand, the depreciation rate and the factor share of input j, while ρ_f is the substitution parameter between inputs. Clearly, the composition of the production function varies depending on the industry: the energy sector requires capital, labour and an energy fossil fuel input;[8] the capital good sector uses energy services and labour; the consumption good sector employs energy services, labour and capital. By solving the cost minimization problem, the nominal demand for additional input reads:

$$H^d_{j,f,t+1} = \mathbb{E}_{f,t}\left[P_{j,t+1}\right]\left[\left(\frac{A_{j,f,t+1}\psi_{f,t+1}}{\mathbb{E}_{f,t}\left[P_{j,t+1}\right]}\right)^{\sigma_f} Q^*_{f,t+1} - (1-\delta_j)X_{j,f,t}\right] \quad \forall j = 1,\ldots,n \tag{9}$$

where

$$\psi_{f,t+1} = \left[\sum_{j=1}^{n}\left(\mathbb{E}_{f,t}\left[P_{j,t+1}\right]\right)^{1-\sigma_f}\left(A_{j,f,t+1}\right)^{\sigma_f}\right]^{\frac{1}{1-\sigma_f}} \tag{10}$$

are the expected marginal costs.

Since firms must pay for production factors in advance, if the expected direct costs are higher than internal liquidity, they seek to obtain external funds by borrowing in a decentralized credit market. If the liquid resources are still insufficient due to credit rationing, firms will determine the optimal input demand that maximizes the attainable production given the liquidity constraints.

3.4. Banking sector

The banking sector provides credit to borrowing firms that need external finance to purchase production inputs. The price of loan depends upon the financial situation of the borrower-lender, while its quantity is determined by capital requirements.[9] In particular, the interest rate on loans charged by bank b to the borrowing firm f at the time t is given by:

$$i_{b,f,t} = i^{CB}_t + \rho^B \frac{L_{f,t}}{NW_{f,t}} + \varrho^B\left(1 - \frac{NW_{b,t}}{\max\limits_{s=1,\ldots,n^B} NW_{s,t}}\right) + \iota^B \frac{NPL_{t-1}}{L_{t-1}}, \tag{11}$$

[8]See the description of the stylized fossil fuel sector in Appendix A.4.
[9]A detailed description of the banking sector can be found in Appendix A.5.

where $\rho^B, \varrho^B, \iota^B > 0$ are interest rate-related parameters. According to (11), the cost of external finance is increasing with the risk-free policy rate i_t^{CB}, the firm's leverage ratio, $L_{f,t}/NW_{f,t}$, and the non-performing loans ratio, NPL_{t-1}/L_{t-1}, while decreasing with the bank's net worth, $NW_{b,t}$.

In line with the Basel III international regulatory framework, banks must comply with macro-prudential capital requirements which define both (i) the total amount of credit that they can extend and (ii) the maximum exposure to a single counterpart. This implies that borrowing firms might be unable to fully satisfy their financing needs, in which case they are forced to scale down the desired production and, subsequently, the input demand.

3.5. Central bank

The central bank sets the risk-free policy rate, i_t^{CB}, following an inertial Taylor rule, that is:

$$i_t^{CB} = \rho^{CB} i_{t-1}^{CB} + (1-\rho^{CB}) \max\left[0,\ r^* + p^* + \lambda^y (u^* - u_{t-1}) + \lambda^p (p_{C,t-1} - p^*)\right]. \tag{12}$$

According to equation (12), the central bank reacts to deviations in inflation and unemployment rates from their target levels, respectively p^* and u^*, given the steady-state interest rate r^*. To avoid abrupt changes in firms' financing conditions, the interest rate is slowly adjusted to the level implied by the Taylor rule, with ρ^{CB} defining the speed of adjustment (Castelnuovo, 2003).

3.6. Government

The government collects taxes (TAX_t) from agents' income (i.e., workers' wages and firms and banks' profits), distributes transfers (TRA_t) to low-income households, and acts as a lender of last resort providing liquidity (EXP_t) to failed banks. If public spending exceeds tax revenues, the government issues additional bonds which are bought by the banking sector. The interest rate paid on public bonds to banks is the risk-free policy rate set by the central bank (i_t^{CB}). Hence, public debt (B_t) evolves according to the following law of motion:

$$B_t = (1 + i_{t-1}^{CB}) B_{t-1} + TRA_t + EXP_t - TAX_t. \tag{13}$$

The dynamics of the debt-to-GDP ratio can be written as:

$$b_{t+1} = \frac{1 + i_t^{CB}}{1 + g_t} b_t - f_{t+1}, \tag{14}$$

where b_t is debt-to-GDP ratio, $f_t \equiv (TAX_t - TRA_t - EXP_t)/GDP_t$ is the primary budget-to-GDP, and g_t is the expected nominal growth rate of GDP. The government must comply with a fiscal sustainability rule that prevents public debt from increasing indefinitely.[10] According to that, the government smoothly adjusts the current debt-to-GPD ratio to a target value b^* at a rate ρ^G as follows:

$$b_{t+1} = b_t + \rho^G (b^* - b_t). \tag{15}$$

By substituting (15) into (14), we obtain the expected primary balance (or planned budget) for the subsequent period, that is:

$$-f_{t+1} = \rho^G b^* + (1-\rho^G)\left[1 - \frac{1 + i_t^{CB}}{(1+g_t)(1-\rho^G)}\right] b_t,. \tag{16}$$

[10] See, for example, the Stability and Growth Pact (SGP) for the European Union member states.

To comply with the expected primary balance resulting from the fiscal rule, the government modifies the level of tax rate, τ_t^{tax}, while leaving unchanged the share of social transfer over GDP, τ_t^{tra}, at a rate ψ^G. The latter can be increased only if the expected primary balance guarantees enough fiscal space, that is:

$$\tau_t^{tra} = \max\left(\psi^G, -f_{t+1}\right), \tag{17}$$

where τ_t^{tra} represents the share of social expenditures and ψ^G is the constant benchmark value.[11] Given τ_t^{tra}, the tax rate for the current period is thus defined as:

$$\tau_t^{tax} = \max\left(0, f_{t+1} + \tau_t^{tra}\right). \tag{18}$$

If negative, the tax rate is set equal to zero, as consumer and firm subsidies are formalized in a different manner (see next section).

4. Energy shocks and policy scenarios

Following the observed increase in the price of natural gas in Europe (+300% annual growth between May 2021 and 2022, source: IMF, Primary Commodity Price System), we characterize the energy price shock as a 300% increase in the price of fossil fuel, followed by an autoregressive process with $\rho^s = 0.8$. Moreover, we calibrate those parameters such that the simulated real GDP loss (including the effect of stabilization policies) one and two years after the shock is in line with the IMF's and the European Commission's downward revision of 2022-2023 growth forecasts (see Table 2).

Table 2: *Revision of expected GDP in the Euro Area: actual vs simulated data.*

Year		**2022**	**2023**
AMECO		−1.21%	−1.32%
IMF		−1.22%	−0.90%
MATRIX	no policy	−5.80%	−1.21%
	policy 1	−1.21%	1.42%
	policy 2	−3.50%	−0.56%

Note: percentage deviation of expected aggregate production in the Euro Area between autumn 2021 and spring 2022 forecasts. Comparison with simulated data in selected policy scenarios, i.e., no policy, SF (policy 1) and medium ET (policy 2), see Table 3). Source: annual macro-economic database of the European Commission's Directorate General for Economic and Financial Affairs (AMECO), autumn 2021 and spring 2022 vintages; International Monetary Fund, World Economic Outlook Database, October 2021 and April 2022 vintages.

Table 3 summarizes the set of policy experiments that we implement in our analysis together with a brief description. They consist of five different macro-stabilization policies, that is tax cuts (TC), household subsidy (SH), firm subsidy (SF), extra-profit tax (XT) and energy tariff reduction (ET).

The simulation protocol is defined as follows. First, we construct the *baseline scenario* (without shock) calibrated on Euro Area data.[12] Then, we simulate the *shock scenario*, i.e., the baseline scenario + energy price shock, and, on top of that, the five *policy scenarios* illustrated in Table 3. For each scenario, we run 250 Monte Carlo replicas of the model with different random seeds

[11]This reflects the stable ratio of social expenditures net of pension spending to GDP observed in countries such as the EA.

[12]The validation procedure is presented in Appendix B.

Table 3: *Policy experiments.*

Label	Macro-stabilization policy	Description
TC	Tax cuts	Reduction in tax rate proportional to % change in GDP
SH	Households subsidy	Transfers to households proportional to loss of income
SF	Firms subsidy	Transfers to firms proportional to loss of profits
XT	Extra-profits tax	Taxation of extra-profits in energy sector
ET	Energy tariffs reduction	Reduced charges on fossil input price

and compute the Impulse Response Functions (IRFs) to compare the model outcomes under shock and policy scenarios with the baseline. In particular, we compute the *percentage deviation* from the baseline for the variables expressed in *in levels* (e.g., GDP, final good price), while the *absolute deviation* for the variables defined in *percentage terms* (e.g., public debt to GDP ratio, unemployment rate).

4.1. Tax cuts & subsidies

We start by analysing the first three policy scenarios, namely tax cuts, household and firm subsidy schemes. Since the aim of these policies is to compensate for agents' loss of income due to energy shocks, they are introduced in $T_{shock}+1$, that is, after the loss was realized.

More specifically, tax cuts apply to all agents in the model, both households and firms, and consist of a percentage reduction in income tax rate proportional to the aggregate GDP loss, computed as the relative deviation of current GDP from its historical level. Household/firm subsidies consist of a transfer to households/firms proportional to their individual income losses, computed as the absolute deviation of current income/profits from their historical level. In symbols:

$$\Delta\tau_t = \min\Big(0, \psi_t^{FP}\left(GDP_t/\overline{GDP}-1\right)\Big), \tag{19}$$

$$S_{h,t} = \min\Big(0, \psi_t^{FP}\left(Y_{h,t}-\overline{Y}_h\right)\Big), \tag{20}$$

$$S_{f,t} = \min\Big(0, \psi_t^{FP}\left(\Pi_{f,t}-\overline{\Pi}_f\right)\Big), \tag{21}$$

where $\overline{GDP}$, $\overline{Y}_h$ and $\overline{\Pi}_h$ are the real medians of aggregate GDP, household h's income and firms f' profits over the last 20 simulation steps (i.e., 5 years) before the shock, then adjusted for current prices. The intensity of fiscal policy is governed by the time-varying parameter ψ_t^{FP}, which is set equal to one in $T_{shock}+1$ and then gradually declines following the AR process of the shock.[13] This means that the government is willing to fully compensate for the income losses accruing in the first quarter of the shock. Afterwards, the policy strength reflects the severity of the energy crisis, captured by the size of the shock, which is assumed to slowly diminish over time.[14] Note that by equations (19)-(21) the level of tax cuts and subsidies is endogenously determined by the extent of the aggregate/individual income loss, with a compensation rate diminishing over time. Therefore,

[13]In our view, this is the most efficient way to formalize the intensity and duration of policy intervention without introducing ad-hoc assumptions on government behaviour and adding further parameters.

[14]In *all* policy scenarios, to provide the government with enough resources without jeopardizing the stability of the economy and the sustainability of its financial position, the speed of adjustment toward the target debt-GDP ratio, ρ^G, is initially set to zero and then gradually converges to the baseline value following the policy intensity, ψ_t^{FP}. In this way, both the strength of stabilization policies and the tightness of budget constraints are governed by the parameter ψ_t^{FP}, which in turn depends on the evolution of the shock.

concerning the subsidy policy, firms and households that experience greater losses will receive more financial support from the government.

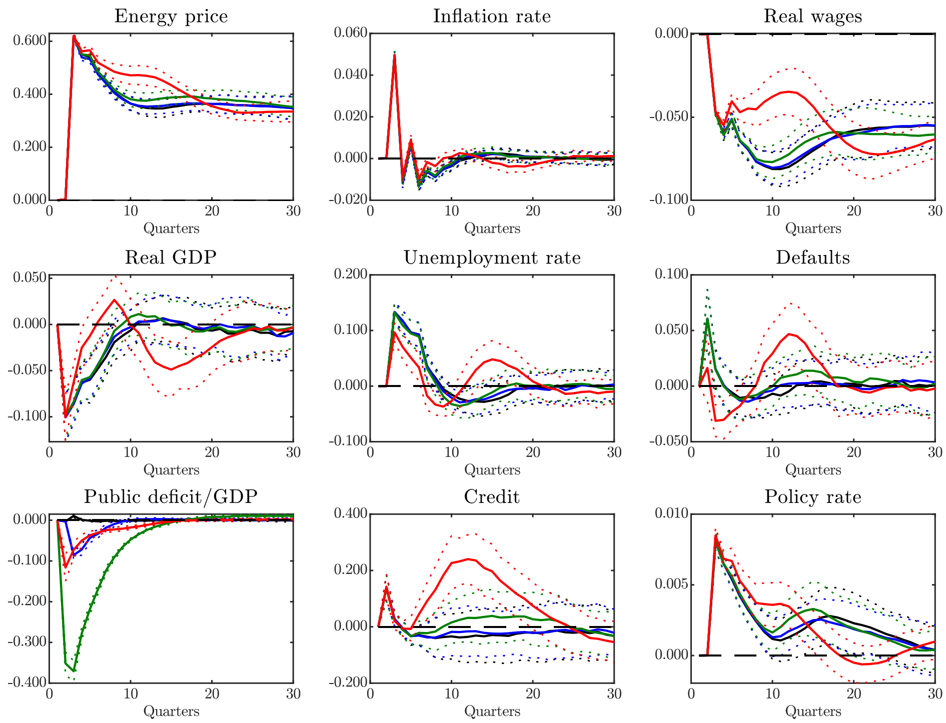

Figure 1: *Macroeconomic effects of energy price shock and policy responses.*

Note: IRFs of the simulated economy to a 300% increase in fossil fuel price. Scenarios: no policy (black); tax cuts (blue); household subsidy (green); firm subsidy (red). Averages (solid lines) and 90% confidence intervals (dotted lines) computed on 250 independent replicas.

Figure 1 compares the economic impacts of tax cuts and household and firm subsidies with the no policy scenario relative to the baseline (without shock). The time unit is a quarter, where quarter zero is the time when the shock hit the economy. We start by assessing the macroeconomic effects of energy price shock in the absence of stabilization policies from the no-policy context (black line) in Figure 1. An exogenous increase in fossil fuel price leads to a spike in inflation rate driven by rising energy prices, which remain above the pre-shock levels. The economy experiences a severe contraction characterized by lower output and employment, followed by a slow recovery. The real GDP declines by nearly -10% in the first quarter and, in the absence of stabilization policies, it takes approximately 12 quarters (i.e., 3 years) to recover to its pre-shock levels. More in detail, the recession originates in the energy sector and then propagates to the rest of the economy via decentralized market interactions. Indeed, given their predefined input budget, E-firms fail to fulfil their fossil fuel demand because of the unexpected price shock, resulting in lower supply and higher price of energy. As a result, the energy shortage induces consumption and capital goods firms to cut back their economic activity and lay off workers. At the same time, the increased production costs due to higher energy prices exacerbate the financial situation of the corporate sector, leading to higher default rates (+5%) due to firms' inability to meet financial obligations. After the initial downturn, the economic system gradually converges to its pre-shock level despite the persistent increase in energy prices. That is due to a *substitution effect* by which firms are encouraged to replace energy inputs with other relatively cheaper factors of production, such as labour and capital. As we exclude ad-hoc changes in the conduct of monetary policy in the present analysis, the central bank reacts to the energy price shock by increasing the policy rate to contain price inflation.[15]

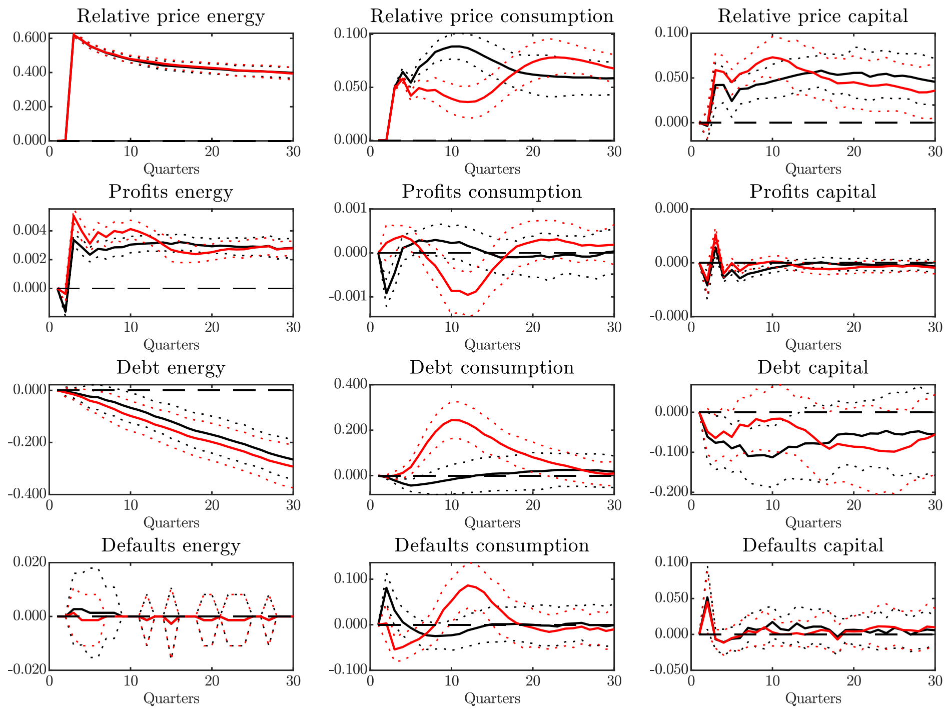

Figure 2: *Sectoral effects of energy price shock and policy responses.*

Note: IRFs of the simulated economy to a 300% increase in fossil fuel price. Scenarios: no policy (black); firm subsidy (red). Averages (solid lines) and 90% confidence intervals (dotted lines) computed on 250 independent replicas.

Moving to stabilization policies, tax cuts (blue) and consumer subsidy (green) do not have a significant impact on economic activity, as the respective curves mostly overlap with the no-policy scenario (black) for the entire period under consideration (see Figure 1). Nevertheless, the consumer subsidy scheme comes with a very high price in terms of soaring public deficit, as shown in the bottom-left pane of Figure 1. The reason is that while this policy involves a significant disbursement of public funds because it targets the whole population of households, its marginal impact on individual consumer spending is relatively small. Indeed, by assumption, energy services are not part of the consumption budget, and therefore households face only the indirect costs of energy shocks via lower real and nominal wages. On the contrary, firm subsidy (red) seems to be the most effective policy in mitigating the adverse effects of energy price increases in the short run. In fact,

[15]We tried alternative monetary policy rules by varying the inertia of the Taylor rule, ρ^{CB}, and the weight given to inflation, λ^p, finding that short-term effects of stabilization policies are essentially similar. Results are available upon request.

by limiting the number of defaults, subsidies paid to firms can shorten the time to recovery and contain the unemployment rate at relatively low public costs. However, under this policy scenario, the economy experiences a second downturn in the medium run, about ten quarters after the initial shock. Indeed, by keeping artificially alive firms that would have defaulted even in the absence of the shock – as manifested by the negative difference in the default rate relative to the baseline –, firm subsidy leads the economy to overheat, fostering a credit-driven expansion that eventually enhances the financial fragility of the system.

To better understand the mechanism behind this second downturn, Figure 2 shows the economic effects of the energy price shock by sector. In particular, economic losses associated with the second downturn are concentrated in the consumption goods sector. Indeed, upstream (energy and capital goods) firms manage to pass on the increase in production costs (spurred by the sharp recovery) to customers, while downstream (consumption) firms fail to do so as they face tighter demand conditions. It follows that C-firms seek to recover the liquidity shortage deriving from falling profits by resorting to debt financing, thus becoming more exposed to the risk of bankruptcy, which eventually materializes almost two years after the shock. In short, we find that firm subsidy is highly effective at promoting a faster recovery by reducing corporate defaults but comes at the cost of greater financial instability in the medium run due to market distortions created by the subsidies.[16]

4.2. Extra-profit tax

Figure 1 and 2 show that an exogenous increase in the fossil fuel price leads to a persistent rise in energy prices, resulting in greater profits for energy firms. A similar trend manifested in Europe in the first half of 2022, where firms operating in the energy sector have seen their profits surge extraordinarily because of the abnormal rise in energy prices. As reported in Table 1, that induced several European countries, such as Bulgaria, Italy, Portugal, Spain and the United Kingdom, to introduce an extra-profit tax to redistribute windfall gains resulting from the energy price hike in favour of the most vulnerable.

We design an excess profit tax resembling the policy introduced by the Italian government in March 2022, Decree-Law No. 67/2022. Since the declared objective of the tax was to collect resources to finance measures in support of households and businesses hit by the shock, we investigate the impact of an extra-profit tax (XT) coupled with firm subsidy, which proved to be the policy delivering the most significant results. Following the Italian government's proposal, the extra-profit tax applies to those firms that experience a positive change in profits above a specific threshold, defined both in level and percentage terms, namely:

$$XT_{f,t} = \begin{cases} \psi_t^{XT}\left(\Delta\Pi_{f,t} - \underline{\Pi}\right) & \text{if } \Delta\Pi_{f,t} > \underline{\Pi} \ \&\ \Delta^{\%}\Pi_{f,t} > \underline{\Pi}^{\%} \\ 0 & \text{otherwise} \end{cases}, \tag{22}$$

where $\Delta\Pi_{f,t} = \Pi_{f,t} - \overline{\Pi}_f$ and $\Delta^{\%}\Pi_{f,t} = \Pi_{f,t}/\overline{\Pi}_f - 1$ are, respectively, the absolute and percentage deviations from the real median profit, $\overline{\Pi}_f$, over the last 20 simulation steps (i.e., 5 years) before the shock, then adjusted for current prices; $\underline{\Pi}$ and $\underline{\Pi}^{\%}$ are the minimum thresholds that define the extent of excess profits, respectively, in level and percentage terms. Specifically, equation (22) states that if a firm f meets both conditions on the right-hand side, it must pay a tax ψ_t^{XT} on the portion

[16] This interesting result relates to the ongoing debate on the risk of "zombification" of the economy due to the unconditional financial support provided to firms by public authorities in response to the Covid-19 shock. See, for instance, Guerini et al. (2022) for the French case and Laeven et al. (2020) for Europe. Banerjee and Hofmann (2018) document the rise of zombie firms in the pre-pandemic era.

of profit variation that exceeds what is deemed to be a normal change.[17] Introduced in $T_{shock}+1$ like the FS, the tax is kept at the initial level for n^{XT} periods and then gradually declines following the AR process of the shock. We simulate three scenarios considering different initial levels of the tax rate, i.e., $\psi_0^{XT}=\{0.1, 0.5, 1\}$, corresponding to a low, medium and high extra-profit tax scenario.

Figure 3 compares the effects of the introduction of an extra-profit tax at different rates coupled with firm subsidy with the no-policy (black) and subsidy only (red) scenarios. As before, the plots report for each scenario the cross-sectional means and bootstrap confidence intervals of the percentage change of key macroeconomic variables from the baseline without shock. The introduction of an extra-profit tax does not have a significant impact on real GDP but, if not too low, alleviates the economic and financial costs of firm subsidy by substantially reducing the level of public debt-to-GDP ratio. In particular, the higher the initial tax rate, the lower the public debt. Consequently, because the enhanced flow of tax revenues helps to ease budgetary constraints, the government can reduce the income tax rate (bottom-right pane), although this has a negligible economic impact in our model.

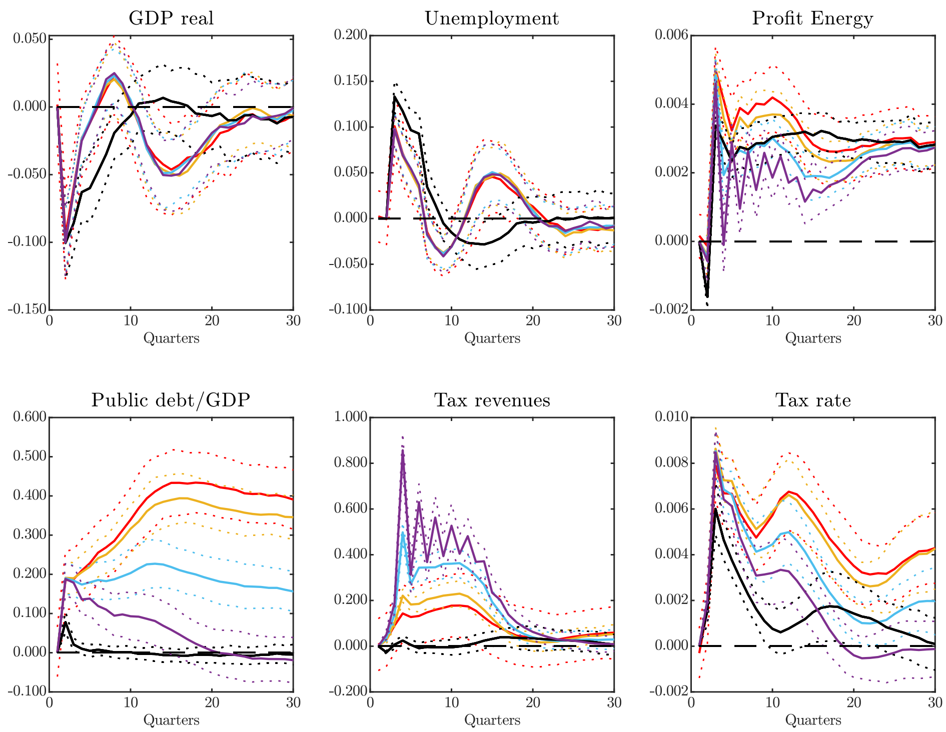

Figure 3: *Macroeconomic effects of energy price shock and extra-profit tax.*

Note: IRFs of the simulated economy to a 300% increase in fossil fuel price. Scenarios: no policy (black); SF only (red); low XT+SF (orange); medium XT+SF (light blue); high XT+SF (purple). Averages (solid lines) and 90% confidence intervals (dotted lines) computed on 250 independent replicas.

Moreover, the top-right pane in Figure 3 shows that, as expected, the introduction of a windfall

[17] The Italian government set $\underline{\Pi}^{\%}$ equal to 10% and $\underline{\Pi}$ equal to €5 mln, which, based on our calculation using Italian energy firm-level data from Compustat, corresponds to roughly 7.75% of the mean of the pre-shock energy firms' profit distribution.

tax determines a significant reduction in energy firms' profits, even if they remain higher than they would have been in the absence of the energy shock. Nevertheless, for a high value of XT, the energy profits dynamics exhibit large fluctuations, which are then reflected in the flow of tax revenues. That happens because, when the windfall tax is too high, the government systematically fails to define the correct measure of extra-profits, oscillating between excessive taxation and the provision of financial support to energy firms from one period to another. Even though such an unstable pattern does not have severe repercussions on the model dynamics because of the simplified version of the energy sector, it is reasonable to think that, in reality, that would cause severe problems for the functioning of the energy market and, subsequently, for the economy as a whole. Therefore, our findings suggest that, if too low, the extra-profit tax would be essentially ineffective in stabilizing public finances. At the same time, if too high, it might risk compromising the financial viability of the energy sector, with likely negative effects on the macroeconomy.

4.3. Energy tariff reduction

Table 1 show that most of the European countries introduced forms of energy tax reductions to contain energy price increases and mitigate the adverse consequences on consumers and businesses. In light of this, in this policy scenario, we investigate the effects of a reduced excise tax on fossil fuel prices, with the government paying the difference between the purchase price for consumers (energy firms) and the selling price set by the producers (fossil fuel sector). In formula:

$$P_{O,t}^{cons} = \left(1 + \tau_t - \psi_t^{ET}\right) \cdot P_{O,t}^{prod}, \tag{23}$$

where $P_{O,t}^{cons}$ and $P_{O,t}^{prod}$ are the fossil fuel price, respectively, paid by the consumers and charged by the producer, τ_t is the excise tax on fossil fuel and ψ_t^{ET} is the extent of energy tax reduction defined by the government.

Contrary to the subsidy which is meant to compensate for income losses once they have occurred, the energy tariff reduction can be effectively implemented in T_{shock} to halt the spike in energy prices. Once introduced, we assume that the tax relief, ψ_t^{ET}, remains in place at the initial level for n^{ET} periods and then gradually declines following the AR process of the shock. As with the extra-profit tax, we simulate three scenarios with different levels of energy tariff reductions, i.e., $\psi_0^{ET} = \{0.05, 0.15, 0.50\}$.

Figure 4 shows the macroeconomic effects of different levels of energy tariff reduction in comparison with the no-policy scenario. If introduced in a timely fashion and at an appropriate level, the energy tax reduction can strongly mitigate the adverse effects of the energy shock without creating the market distortions brought about by firm subsidies. By containing the spike in energy prices, this policy allows tackling the root causes of the crisis, leading to higher real wages and lower firms' defaults, with positive effects on consumer spending, GDP and employment. In terms of public finances, the higher the tariff reduction, the higher the public deficit to GDP. Nevertheless, the amount of resources needed to fund a 50% tariff reduction (high ET scenario) is approximately one order of magnitude lower than the firm subsidy.

4.4. Overall policy comparison

Figure 5 presents an overall comparison of the stabilization policies in terms of time for the GDP to complete recovery (in quarters) and related change in the public debt-to-GDP ratio. In addition to the individual experiments discussed above, we also consider two scenarios characterized by a combination of policy measures: policy mix 1 combines energy tariff reduction and extra-profit

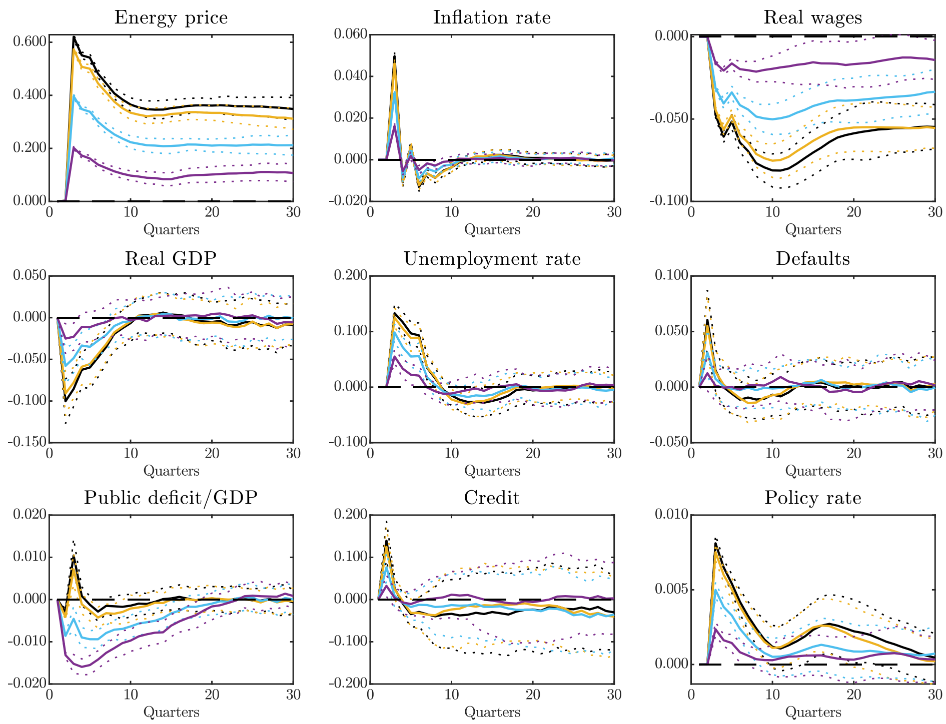

Figure 4: *Macroeconomic effects of energy price shock and energy tariff reduction.*

Note: IRFs of the simulated economy to a 300% increase in fossil fuel price. Scenarios: no policy (black); low ET (yellow); medium ET (light blue); high ET (purple). Averages (solid lines) and 90% confidence intervals (dotted lines) computed on 250 independent replicas.

tax (EXT); on top of that, policy mix 2 includes also firm subsidy (EXT + SF). Notice that firm subsidy is undoubtedly the most effective policy to promote a faster recovery, almost halving the time required to reach the pre-shock GDP level, especially if combined with ET and XT, as in the policy mix 2 scenario. Also, energy tariff reduction, alone and in combination with an extra-profit tax (policy mix 1), allows to speed up recovery at even lower public costs. However, the boxplots for these policy scenarios exhibit larger volatility across simulations, suggesting that the ability of ET to prompt a rapid recovery is more uncertain compared to the firm subsidy.

The plots in Figure 5 provide a synthetic overview of the short-run effects of the stabilization policies. To evaluate their economic impacts on a longer time horizon, we compute a measure of social welfare, defined as the sum of (log) individual real consumption expenditure by households. Figure 6 shows for each policy experiment the change in social welfare relative to the no-policy scenario, both over time (left pane) and the discounted value at T_{shock} (right pane). We can see that social welfare is maximized under the ET scenarios, while it is somewhat lower in the presence of firm subsidy. That is because, whereas both these policies entail welfare-enhancing effects in the short run, the second downturn resulting from the market distortions created by the subsidy brings down household welfare in the medium term.

Consumer subsidy is clearly an inferior policy option in our model also in terms of social welfare. Indeed, as shown in Figure 1, this policy entails a significant disbursement of public resources with no significant impact on aggregate economic activity. The resulting increase in the public debt to GDP ratio induces the government to face tighter budgetary constraints and raise the tax rate, which eventually undermines household income and consumption expenditure.

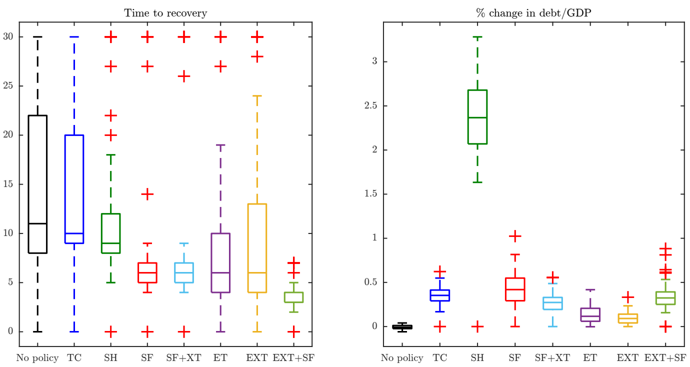

Figure 5: *Time to recovery and change in public debt-to-GDP.*

Note: box plots of the time to recovery (left pane) and the change in public debt-to-GDP (right pane) in the simulated economy after a 300% increase in fossil fuel price. Scenarios: no policy (black); tax cuts (TC, blue); household subsidy (SH, green); firm subsidy (SF, red); extra-profit tax (medium-XT, light blue); energy tariff reduction (high-ET, purple); policy mix 1 (ET+XT, yellow); policy mix 2 (ET+XT+SF, green). Results computed on 250 independent replicas.

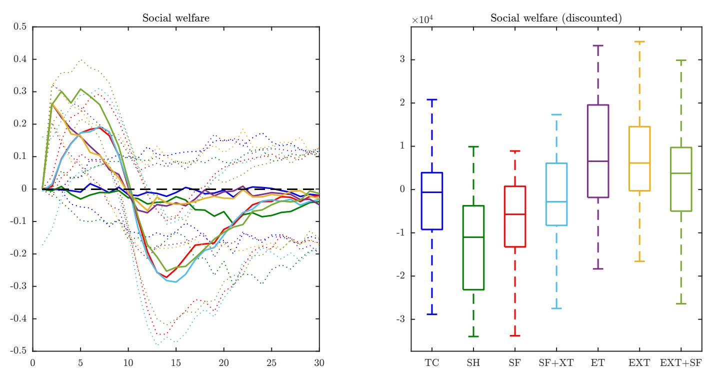

Figure 6: *Social welfare and policy scenarios.*

Note: instantaneous (left pane) and discounted (right pane) variation of aggregate social welfare between no policy scenario and policy interventions. Scenarios: tax cuts (TC, blue); household subsidy (SH, green); firm subsidy (SF, red); extra-profit tax (medium-XT, light blue); energy tariff reduction (high-ET, purple); policy mix 1 (ET+XT, yellow); policy mix 2 (ET+XT+SF, green). Results computed on 250 independent replicas.

4.5. Distributional impacts of energy price shock and stabilization policies

So far, we have examined the economic effects of different types of macro-stabilization policies in response to energy price increases at the aggregate and sectoral levels. Departing from the representative agent hypothesis of the standard approach, a key feature of ABMs lies in the heterogeneity of agents' characteristics and behavioural rules, which allows addressing several issues related to income inequality and market structure (Caiani et al., 2019; Terranova and Turco, 2022). In this section, we exploit this feature of the model to investigate how the energy price shock and related stabilization policies impact the wealth distribution of heterogeneous agents.

Figure 7 compares the distributions of individual wealth changes one year after the shock for workers (left panes) and energy firms owners (right panes) under the scenarios of no policy, tax cuts (TC), household subsidy (SH) and firm subsidy (FS) relative to the baseline. To highlight the specific contribution of each policy, the bottom panes display the difference in the probability distribution of the three policy scenarios from the no-policy one. On average and independently of the stabilization policy, the energy price shock entails opposite effects on agents' wealth, negative for workers and positive for energy entrepreneurs. Indeed, nominal and real wages slow down because of the spike in unemployment and inflation rates caused by the shock. At the same time, the increase in energy prices boost energy firms' profits, resulting in higher dividend payments and thus financial wealth for energy entrepreneurs. Nevertheless, the left skewness of the wealth distribution under the no-policy scenario indicates that not all energy firm owners benefit from the shock: a consistent share of individuals sees no changes in wealth compared to the baseline, suggesting that the economic gains are not equally distributed among energy firms. This effect disappears under the FS scenario (red), where the distribution of energy entrepreneurs' wealth changes becomes more symmetrical. Indeed, by limiting the number of bankruptcies, subsidies paid to firms help stabilize corporate profits, with positive effects for the energy sector both directly and through the improvement of the financial situation in other industries. Also, tax cuts slightly improve the wealth of energy firm owners, especially for the benefit of those who would experience minor positive changes in wealth without policy. Interestingly, only household subsidy has a positive impact on workers' wealth distribution, albeit irrelevant from a macroeconomic perspective as seen in Figure 1.

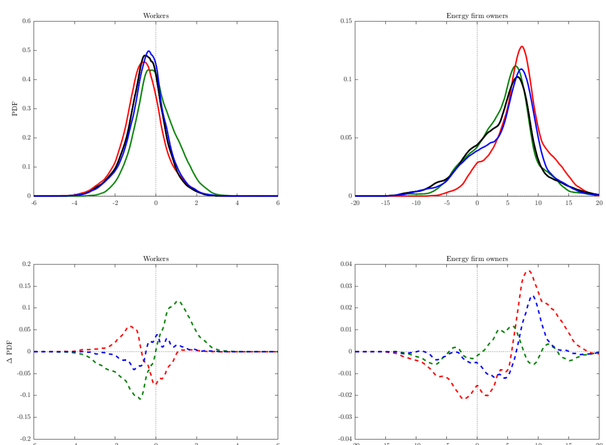

Figure 7: *Distributional effects of energy price shock and stabilization policies.*

Note: distributional effects of the energy shock on workers (left panes) and energy entrepreneurs (right panes). Probability density functions (upper panes) and deviations from the baseline (no shock) scenario (lower panes) of income variation one year after the shock. Scenarios: no policy (black); tax cuts (blue); household subsidy (green); firm subsidy (red). Results computed on 250 independent replicas.

Figure 8 shows the distributive effects of a windfall profits tax on energy firms for workers and energy entrepreneurs one year after the shock. Unsurprisingly, the introduction of an extra-profit tax, by narrowing the net profits of the energy sector, leads to a lower increase in the wealth of energy entrepreneurs, following the extra tax rate, with no sensible effects on workers' wealth. A similar result is obtained under the ET scenario as shown in Figure 9. In addition, by containing the energy price increase and limiting its adverse effects on the economy (see 4), a reduced excise tax on fossil fuel prices leads to a sizeable improvement in workers' wealth, especially for a high value of tariff cuts. Hence, energy tax reduction seems to be the most effective policy to mitigate the economic impact of an energy price increase and reduce the ensuing rise in income inequality.

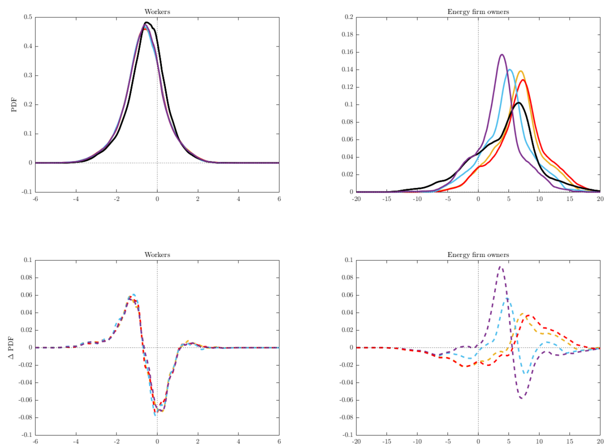

Figure 8: *Distributional effects of energy price shock and extra-profit tax.*

Note: distributional effects of the energy shock on workers (left panes) and energy entrepreneurs (right panes). Probability density functions (upper panes) and deviations from the baseline (no shock) scenario (lower panes) of income variation one year after the shock. Scenarios: FS (red); low XT+FS (yellow); medium XT+FS (light blue); high XT+FS (purple). Results computed on 250 independent replicas.

To conclude, Figure 10 shows for each policy scenario the percentage change in wealth by agent group relative to the baseline at two points in time, that is, one year (top pane) and three years (bottom pane) after the shock.[18] Energy entrepreneurs benefit from an energy price shock in all policy scenarios. That is especially true in the presence of tax cuts and subsidies, where their financial wealth nearly doubles three years after the shock as a consequence of soaring energy profits. By keeping energy prices under control, a fossil fuel tax reduction promotes the redistribution of wealth from energy entrepreneurs to workers, especially if coupled with an extra-profit tax. Interestingly, bankers benefit from the credit-driven recovery spurred by firm subsidies, at the expense of downstream firm owners who experience significant wealth losses three years after the shock since they have to pay the cost of the second downturn fuelled by market distortions.

[18]The plots report the average value of percentage wealth change from the baseline without shock across 250 Monte Carlo simulations.

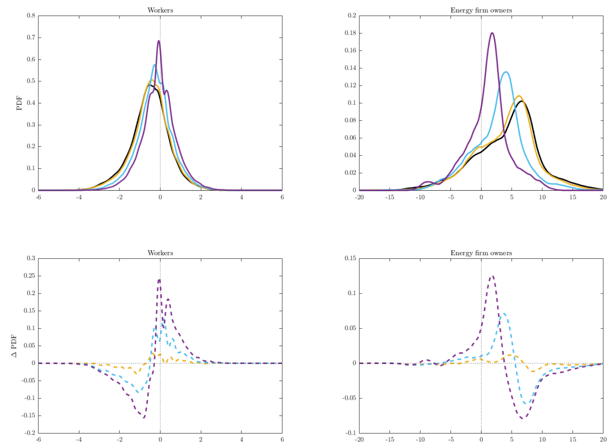

Figure 9: *Distributional effects of energy price shock and energy tariff reduction.*

Note: distributional effects of the energy shock on workers (left panes) and energy entrepreneurs (right panes). Probability density functions (upper panes) and deviations from the baseline (no shock) scenario (lower panes) of income variation one year after the shock. Scenarios: low ET (yellow); medium ET (light blue); high ET (purple). Results computed on 250 independent replicas.

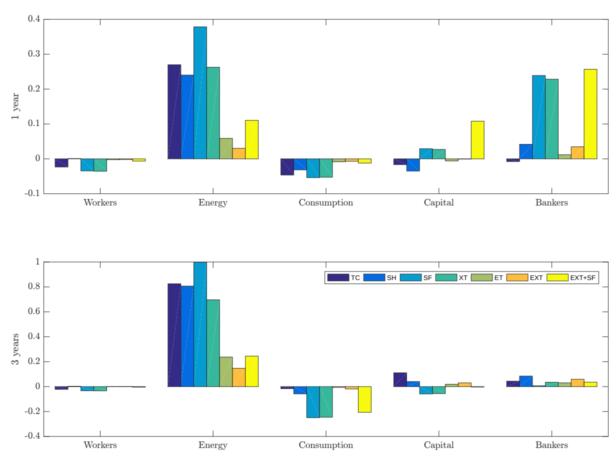

Figure 10: *Percentage change in wealth by agent group.*

Note: average percentage change of wealth from the baseline (no policy) scenario under different policy interventions by agent group one (upper pane) and three (lower panes) years after the energy shock. Results computed on 250 independent replicas.

5. Conclusion and Policy implication

This work introduces an energy price shock to the macroeconomic agent-based model MATRIX (Multi-Agent model for Assessing Transition Risks) calibrated to depict the European Area at the onset of the 2021–2022 energy crisis. The shock entails negative consequences for the simulated economy, resulting in sharp consumer price inflation, a decrease in real GDP, increased firms' defaults and a higher unemployment rate. As a response, a battery of counteracting short-term policies (i.e., non-structural or unrelated to a switch in energy production technologies) is tested. The interventions under consideration, which are a stylized version of the majority of the policy answers in Europe (Sgaravatti et al., 2021), are a general tax rate cut, households' subsidies, firms' subsidies, an extra-profit tax for energy firms, an energy tariff reduction on the fossil fuel input, and two different policy mixes (energy tariff reduction and extra profit tax in the first mix; adding firms subsidies to the former in the second mix).

The agent-based features of the model allow us to evaluate different policy scenarios using multiple evaluation criteria (time to recovery, change in public debt to GDP ratio, and social welfare), as well as consider their distributional impact on the agents. According to our findings, tax cuts and consumer subsidies are ineffective because the economy does not recover as quickly as it would in the absence of those policies, while also increasing the national debt. On the contrary, subsidies to firms provide a faster recovery but result in a second economic downturn in the medium term due to the economy's credit-driven expansion, which inflates and pops financially fragile firms. An extra-profit (or windfall) tax on top of the firm's subsidy maintains the same dynamic while relieving the strain on public debt. The energy tariff reduction can dampen the negative impact of the shock with no further downturn and at a lower cost to the public finances. In terms of time to recovery, the subsidies to firms are the quickest, especially when combined with the energy tariff reduction and the extra profit tax. In turn, the reduction in energy tariffs and the two mixes provide superior equilibria in terms of social welfare. Indeed, in the medium term, the firm's subsidies discount the effects of the second recession.

From the distributional point of view, the shock affects, on average, the workers negatively and the entrepreneurs positively in the energy sector. However, economic gains are not distributed equally among energy entrepreneurs, with the firm subsidy policy making the distribution more symmetrical. As expected, the windfall profit tax reduces wealth for energy entrepreneurs; the energy tariff also displays this effect but reduces income inequality for workers. Overall, energy entrepreneurs stand to gain in all of the policy scenarios. Bankers also benefit most from the expansion in credit in the firms' subsidies scenario.

We can infer several policy implications from this analysis. First, subsidies to firms are the quickest way to recover the economy, but the policymaker should consider their effects on firms' financial fragility, as exemplified here by the second crisis in the medium term. The energy tariff reduction emerged as the most effective answer; coupled with an extra profit tax it can also erode the distributional inequality exacerbated by the price shock. As a result, the extra-profit tax is a valuable instrument to be considered in tandem with other policies. However, it needs careful formulation: a sensitivity analysis on the tax level shows that a level too low might not have any effect on the economy, while a too high one makes it difficult for the government to correctly assess the extra profits, bringing uncertainty on the financial viability of the energy services sector. While tax cuts and household subsidies are ineffective in this analysis, we believe that further work should be conducted before discarding these instruments, perhaps in settings that allow a more direct link between the energy shock and the households' budget.

The main limitation of this work is the lack of a link between energy and the consumer's side, as most of the worries about the energy crisis pertain to the direct effect of rising bills on the household's budget. Moreover, most of the tested policies are stylized representations of the ones adopted in Europe, which might also differ in some details from country to country. It would also be interesting to characterize the policies as more agent-specific, for instance, by making the tax cuts proportional to the agent's wealth.

Future work plans to address these limitations and further expand the MATRIX model to include a fully-fledged climate box and a more detailed energy sector. That would make it possible to study the shocks and policy implications in the context of the energy transition. This is a topic of paramount importance in the EA, considering that the rise in energy prices might affect the transition to renewable energy, as well as revamp the use of carbon-intensive fuels such as coal (Ari et al., 2022). Undoubtedly, further study of policy answers to contrast energy shocks and crises is needed in the current situation of uncertainty and inflationary concerns.

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A. Description of the model

A.1. Households

At each time t, given their consumption budget $H^d_{h,t}$, households visit a subset $\mathcal{Z}^C_{h,t}$ of C-firms chosen at random and purchase goods from the firms offering the largest amount, given the buyer's budget and the sellers' prices and quantities (see Appendix A.3 for the mechanism used by firms to adjust price and supply quantity). If the amount of goods sold by firms is lower than the consumption budget, consumers accumulate involuntary savings.

The nominal income $Y_{h,t}$ of household h at the time t depends on her type (i.e., worker, entrepreneur or banker):

$$Y_{h,t} = \begin{cases} W_t N_{w,t} & \text{for workers} \\ DIV_{f,t} - REC_{f,t} & \text{for entrepreneurs} \\ DIV_{b,t} - REC_{b,t} & \text{for bankers} \end{cases}, \tag{24}$$

where W_t is the wage rate, $N_{w,t}$ the supply of labour of worker w, $DIV_{f,t}$ and $DIV_{b,t}$ are the dividends distributed by firms and banks, and $REC_{f,t}$ and $REC_{b,t}$ are the recapitalization costs borne by the f-th entrepreneur and the b-th banker.

Since the government collects taxes on private agents' income and distributes social transfers to poor households (see Section 3.6), the net income $Y^{net}_{h,t}$ of the h-th household is given by the maximum between after-tax income and the social transfer received:

$$Y^{net}_{h,t} = \max\left[(1-\tau^{tax}_t)Y_{h,t}, TRA_{h,t}\right]. \tag{25}$$

To determine their consumption demand, households adopt an adaptive learning rule to estimate a measure of their permanent income $\bar{Y}_{h,t}$ (Assenza et al. (2015)):

$$\bar{Y}_{h,t} = (1-\xi)Y^{net}_{h,t} + \xi\left(1+\mathbb{E}_t[p_{C,t}]\right)\bar{Y}_{h,t-1}, \tag{26}$$

where $\xi \in (0,1)$ is a memory parameter and $\mathbb{E}_t[p_{C,t}]$ is the expected inflation rate on consumption goods.[19] According to (26), the permanent income is given by a weighted average of current and past income levels, updated by expected inflation, with geometrically decaying weights.

Then, the consumption budget can be expressed as a linear combination between permanent income and a fraction of accumulated deposits:

$$H^d_{h,t} = \mathbb{E}_{h,t}[P_{C,t}]C^d_{h,t} = \bar{Y}_{h,t} + \chi D_{h,t}, \tag{27}$$

where $\chi \in (0,1)$ is the marginal propensity to consume out of financial wealth (Godley and Lavoie, 2006).[20] The difference between income and actual consumption is involuntary saving which increases the existing deposits:

$$D_{h,t} = D_{h,t-1} + Y^{net}_{h,t} - H_{h,t}, \tag{28}$$

where $0 \leq H_{h,t} \leq H^d_{h,t}$ is the actual consumption resulting from the matching process in the consumption good market.

[19]Prices are expected at this stage since consumers do not know the actual values they will find in the market. Here we assume that households use the expected growth rate of consumption goods $\mathbb{E}_t[p_{C,t}]$ (see Appendix A.3) to predict current prices, namely: $\mathbb{E}_{h,t}[P_{C,t}] = (1+\mathbb{E}_t[p_{C,t}])\mathbb{E}_{h,t}[P_{C,t-1}]$, where $\mathbb{E}_{h,t}[P_{C,t-1}]$ is the price observed by consumer h at the time $t-1$.

[20]The consumption budget thus defined can be seen as a reduced form solution of a utility maximization problem with log-utility function, see Ciola et al. (2022b) for detailed proof.

A.2. Labour Market

In the labour market, firms hire and fire workers at no cost given their labour demand, while workers supply up to one unit of labour inelastically given the wage rate. Since job seekers have limited information on market conditions because they can visit only a subset of firms, search frictions may prevent the adjustment of labour to market equilibrium, causing unfulfilled demand and supply. Therefore, when the labour market closes, the wage rate is adjusted through an insider-outsider bargaining process (Dosi et al., 2010), which depends on prevailing labour market conditions and inflation expectations.

More precisely, given the labour supply N_t^s (i.e., the total number of workers, $N_t^s = n^W$), the aggregate labour demand N_t^d (i.e., the sum of firms' optimal labour demands, $N_t^d = \sum N_{f,t}^d$) and the current amount of hours worked N_t^{emp}, the wage rate for the following period W_{t+1} is defined as:

$$W_{t+1} = (1 + w_{t+1})W_t = \rho^W W_t + (1 - \rho^W) \left[\theta^W \left(\frac{N_t^d}{N_t^{emp}}\right) + (1 - \theta^W) \left(\frac{N_t^{emp}}{N_t^s}\right)\right] W_t + \mathbb{E}_t \left[p_{C,t+1}^{anc}\right] W_t, \quad (29)$$

where ρ^W is a fraction of the new wage unaffected by current labour market conditions. The remaining part $(1 - \rho^W)$ depends on the insider-outsider bargaining power θ^W as follows: the higher the labour demand over current employment, the faster the wage growth (insiders' objective); while the higher the labour supply respect to current employment, the lower the wage growth, positively affecting the employment rate (outsiders' objective). According to (29), the nominal wages growth rate accounts for inflation expectation $\mathbb{E}_t[p_{C,t+1}^{anc}]$, which is anchored to the central bank inflation target p^*, namely:

$$\mathbb{E}_t \left[p_{C,t+1}^{anc}\right] = \iota^W \mathbb{E}_t \left[p_{C,t}\right] + (1 - \iota^W) p^*, \quad (30)$$

where $\mathbb{E}_t[p_{C,t}]$ is the expected inflation of C-goods for the current period (see Appendix A.3) and ι^W is a decaying weight (Yetman, 2017; Mehrotra and Yetman, 2018).

A.3. Firms

Price and quantity adjustment Since agents can only visit a subset of the market, firms do not know their demand in advance. Therefore, each firm forms expectations about future demand based on their past economic performance adaptively revising a $\{P, Q\}$ strategy to achieve higher profits. Under these conditions, there is no unique price-quantity $\{P, Q\}$ combination that guarantees the market equilibrium.

In line with the macro ABM literature,[21] we assume that firms set the desired combination of price and quantity by imitating the $\{P, Q\}$ strategy of similar competitors, if more successful, or by exploring a neighbour of their current strategy according to past excess demand.

Similarity is defined as the distance $(d_{s,f,t})$ between firm f and all the other firms $s \neq f \in n^F$ belonging to the same sector $F = \{E, C, K\}$. Its value is measured as the difference between firms' relative positions in the firm size distribution in terms of nominal production, namely:

$$d_{f,s,t} = \left|\hat{y}_{f,t} - \hat{y}_{s,t}\right|, \quad (31)$$

where $\hat{y}_{f,t} \equiv \frac{P_{f,t}Q_{f,t} - \min(P_{f,t}Q_{f,t})}{\max(P_{f,t}Q_{f,t}) - \min(P_{f,t}Q_{f,t})}$.

[21] See, among others,(Delli Gatti et al., 2011; Assenza et al., 2015; Riccetti et al., 2014; Caiani et al., 2016; Ciola et al., 2022a)

The target competitor is obtained through a weighted sampling from the list of all firms but f, with probability weights given by:

$$\Pr(s = S|f,t) = \frac{\exp(-\omega \cdot d_{f,S,t})}{\sum\limits_{s \neq f \in n^F} \exp\left(-\omega \cdot d_{f,s,t}\right)}, \tag{32}$$

where $\omega > 0$ represents the intensity of choice, i.e., how fast firms target the closest competitor in the distribution. According to (32), the probability for firm f of observing the target competitor s is decreasing with their distance $d_{f,s,t}$. Once the target competitor S is identified, the firm f updates its desired quantity and price for the subsequent period $\{Q^*_{f,t+1}, P_{f,t+1}\}$ as follows:

$$Q^*_{f,t+1} = \begin{cases} \zeta^Q Q^*_{f,t} + (1-\zeta^Q) Q_{S,t} & \text{if } \Pi_{S,t} \geq \Pi_{f,t} \\ \zeta^Q Q^*_{f,t} + (1-\zeta^Q) \hat{Q}_{f,t} & \text{otherwise} \end{cases}, \tag{33}$$

$$P_{f,t+1} = \begin{cases} \zeta^P P_{f,t} + (1-\zeta^P) P_{S,t} & \text{if } \Pi_{S,t} \geq \Pi_{f,t} \\ \zeta^P P_{f,t} + (1-\zeta^P) \hat{P}_{f,t} & \text{otherwise} \end{cases}, \tag{34}$$

with ζ^Q and ζ^P representing the adjustment speeds of quantity and price, $\hat{Q}_{f,t} = Q^*_{f,t} \cdot [1 + U \cdot \Delta_{f,t}]$ and $\hat{P}_{f,t} = P_{f,t} \cdot [1 + U \cdot \Delta_{f,t}]$ are a neighbourhood of current desired quantity and price, with U being a random drawn from a uniform distribution and $\Delta_{f,t} = (Q^d_{f,t} - Q^*_{f,t})/Q^*_{f,t}$ the percentage deviation of observed demand $Q^d_{f,t}$ from past desired production $Q^*_{f,t}$.

Following the *evolutionary algorithm of price-quantity setting with strategic complementarities* described by (33) and (34), if the profits realized by the target firm S are higher than f's, the f-th firm smoothly adjusts price and desired quantity towards the target's values. Otherwise, the f-th firm updates its strategy by exploring the neighbourhood of the current desired quantity and price. Thus, the excess demand ($\Delta_{f,t}$) affects both the direction and the magnitude of price and quantity adjustments, as in Assenza et al. (2015) and Delli Gatti and Reissl (2022).[22] In other words, firms seek to maximize profits either by locally searching for the most successful competitors and, if more profitable, mimicking their $\{P, Q\}$ strategy, or by adjusting their current strategy according to past excess demand.

Lastly, all prices are revised to account for future changes in sectoral marginal costs aiming to maintain the firms' mark-ups unchanged. In this way, firms strive to maintain their mark-ups unchanged. It follows that the expected growth of nominal prices in sector $F = \{E, C, K\}$ is:

$$\mathbb{E}_t[p_{F,t+1}] = \frac{\mathbb{E}_t\left[\psi_{F,t+1} \mid w_{t+1}, p_{O,t+1}\right] - \psi_{F,t}}{\psi_{F,t}}, \tag{35}$$

where $\psi_{F,t}$ are the average marginal costs of sector F at the time t and $\mathbb{E}_t\left[\psi_{F,t+1} \mid w_{t+1}, p_{O,t+1}\right]$ is their expected value in the subsequent period given the expected change in wages $\mathbb{E}_t[w_{t+1}]$ and fossil fuel price $\mathbb{E}_t[p_{O,t+1}]$ (see Appendix A.2 and A.4).

Production technology We assume that firms use a CES technology (Arrow et al., 1961) with constant returns to scale and diminishing marginal returns.[23] The production function of a generic

[22] To avoid abrupt changes in price and quantity due to unexpectedly large excess demand, we impose an upper (lower) bound on upward (downward) adjustments so that the actual price and quantity update is given by $\Delta_{f,t} = \min(\gamma^{PQ}, \Delta_{f,t})$ in case of excess demand ($\Delta_{f,t} > 0$), or $\Delta_{f,t} = \max(-\gamma^{PQ}, \Delta_{f,t})$ in case of excess supply ($\Delta_{f,t} < 0$).

[23] While the Leontief and the Cobb-Douglas production functions are a common standard in the ABM literature, we adopt the CES production function because: (i) it reduces to the Leontief and the Cobb-Douglas cases under specific assumptions (i.e., it reduces to a Cobb-Douglas for $\sigma_f = 1$, a Leontief function when $\sigma_f = 0$); (ii) it increases the flexibility of the model and improves its empirical validation.

firm f at the time t is defined as follows:

$$Q_{f,t} = Z_{f,t} \left[\sum_{j=1}^{n} A_{j,f} \left(X_{j,f,t} \right)^{\rho_f} \right]^{\frac{1}{\rho_f}}, \tag{36}$$

where $X_{j,f,t}$ is the quantity of input $j = 1, \ldots, n$ in the firm f at the time t, $\sum_{j=1}^{n} A_{j,f} = 1$ are the factor shares, $\rho_f = \frac{\sigma_f - 1}{\sigma_f}$ is the substitution parameter, σ_f is the Hicks elasticity of substitution and $Z_{f,t} = 1$ is total factor productivity.[24]

The specification of the production function and the related parameter values vary across sectors. More precisely, E-firms require capital, labour and fossil fuel to generate energy services; K-firms require labour and energy services to produce capital goods; C-firms require energy services, labour and physical capital to produce final consumption goods.

Credit demand Firms have to pay for production factors in advance and finance the difference between expected direct costs of production (defined as in (9)) and the total amount of available liquid resources through external finance. Hence, the firm's demand for credit ($\Delta L^d_{f,t+1}$) is given by:

$$\Delta L^d_{f,t+1} = \mathbb{E}_{f,t} \left[DC_{f,t+1} \right] - D_{f,t}, \tag{37}$$

where $D_{f,t}$ are deposits.

Firms try to secure bank credit in a decentralized market and repay the principal at a fixed instalment rate θ^B. Accordingly, firms do not have to pay off all the outstanding debt before they can access new credit lines and, if needed, they can keep refinancing loans at the current interest rate every time. As a result, firms' debt and deposits update according to the following laws of motion:

$$L_{f,t+1} = \Delta L_{f,t+1} + (1 - \theta^B) L_{f,t}, \tag{38}$$

$$D_{f,t} = \Delta L_{f,t+1} + D_{f,t}, \tag{39}$$

where $L_{f,t}$ is total debt, and $0 \leq \Delta L_{f,t+1} \leq \Delta L^d_{f,t+1}$ is the new credit line. If liquid resources are still insufficient to purchase production inputs (i.e., $D_{f,t} < \mathbb{E}_{f,t} \left[DC_{f,t+1} \right]$), firms reduce proportionally their nominal demands:

$$\bar{H}^d_{j,f,t+1} = \upsilon_{f,t+1} H^d_{j,f,t+1} - (1 - \upsilon_{f,t+1})(1 - \delta_j) \mathbb{E}_{f,t} \left[P_{j,t+1} \right] X_{j,f,t} \quad \forall j = 1, \ldots, n, \tag{40}$$

with

$$\upsilon_{f,t+1} = \frac{D_{f,t} + \sum_{j=1}^{n} \mathbb{E}_{f,t} \left[P_{j,t+1} \right] (1 - \delta_j) X_{j,f,t}}{\psi_{f,t+1} Q^*_{f,t+1}}, \tag{41}$$

where $\upsilon_{f,t+1}$ is the ratio between the available liquid resources and the expected total costs.

Profits, net worth and bankruptcy Once the reference market closes, the firms compute profits as revenues net of direct costs for employed inputs and debt service. The equations of profits and net worth accumulation are defined as:

$$\Pi^{net}_{f,t} = (1 - \tau^{tax}_t) \left(P_{f,t} Q_{f,t} - DC_{f,t} - \sum_{b=1}^{n^B} i_{f,b,t} L_{f,b,t} \right), \tag{42}$$

$$NW_{f,t} = NW_{f,t-1} + \Pi^{net}_{f,t} - DIV_{f,t}, \tag{43}$$

[24] We normalize total factor productivity equal to one for the sake of simplicity.

with τ_t^{tax} being the tax rate on profits and $DIV_{f,t}$ the fraction of equity paid by solvent firms to their owners in the form of dividends, namely:

$$DIV_{f,t} = \max\left[0, \min\left(\mu^F NW_{f,t}, D_{f,t}\right)\right], \tag{44}$$

where $\mu^F = 1 - \beta^F$ is the payout ratio of firms.

A firm might default when it becomes either insolvent (i.e., the net worth turns negative, $NW_{f,t} < 0$) or illiquid (i.e., the deposits are negative, $D_{f,t} < 0$). If the firm is illiquid but the owner has sufficient resources to cover the liquidity shortage (i.e., $D_{h,t} > |D_{f,t}|$), the entrepreneur recapitalises the suffering firm. In the other cases, the firm is declared bankrupt and, to keep the number of agents constant, is replaced by a new entrant as in Gertler and Kiyotaki (2010) and Dosi et al. (2013). The entrant's initial conditions are set in the following way: (i) the residual deposits of the bankrupt firm are used to partly repay the outstanding debt; (ii) the entrepreneur seeks to buy out the assets of the old firm at their historical cost by using her personal wealth and, if not sufficient, by asking for a new bank loan in the credit market; (iii) the lending bank records a loss equal to the difference between the funds raised by the entrepreneur and the remaining value of the debt. Thus, the balance sheet of the new firm will have: on the asset side, the purchase value of the assets that the entrepreneur managed to buy out from the old firm and, on the liability side, the value of the new loan (if present).

A.4. Fossil fuel sector

Energy firms purchase fossil fuel at a fixed relative price to wages from a stylized foreign fossil fuel sector with no capacity constraints as in Ponta et al. (2018).[25] In other words, the quantity of fossil fuel is determined by the E-firms demand, while the price growth follows wage inflation adapting to mutated economic conditions (i.e., $p_{O,t+1} = w_{t+1}$, see Appendix A.2). To close the model, the returns from the fossil fuels sales, net of taxes, are redistributed partly to energy firms (η^O) in the form of additional revenues and partly to households ($1 - \eta^O$) as supplementary income. That is to take into account the fact that part of oil and gas production is carried out domestically by energy firms through onshore or offshore activities (η^O), while the remaining share is imported from abroad ($1 - \eta^O$). In this way, our model can account for fossil fuel production and consumption without overly complicating the baseline framework.[26]

A.5. Banks

The banking system is populated by (n^B) heterogeneous banks. Banks supply credit to the corporate sector and make profits by charging differentiated interest rates on loans, hold firms' and households' deposits and buy the T-bills issued by the government in proportion to their net worth. We assume that, in each period, firms repay a fraction θ^B of the principal plus interests on outstanding loans.

Interest rate The interest rate charged by banks to borrowers is in line with the external finance premium hypothesized by Bernanke et al. (1999) but adds some important features. The firm-specific interest rate on loans is a mark-up on the risk-free interest rate and depends on the firms' financial

[25]We set the initial price of the fossil fuel input such that the aggregate fossil fuel expenditure over GDP in the model is the same as the average value observed in the EA between 2001 and 2019, namely 4% (source: authors' calculation on Eurostat data).

[26]As a future line of research, we plan to endogenize the fossil fuel production and enrich the energy sector with a variety of energy plants and production technologies (e.g., green and brown), including a more realistic matching protocol for the electricity markets.

fragility, as in the financial accelerators developed by Grauwe and Macchiarelli (2015), Assenza et al. (2015) and Delli Gatti and Desiderio (2015). Moreover, the financial soundness of the bank plays a role in the definition of its credit policy: a higher financial strength (i.e., higher equity ratio) allows for setting more favourable terms for extending credit (Delli Gatti et al., 2010). The last component of (11) links the cost of external finance to the financial soundness of the banking sector as a whole. As the amount of non-performing loans increases, banks raise the cost of external finance, increasing credit rationing.

Prudential regulation Following the Basel III international regulatory framework, each bank b is subject to the compliance with macro-prudential requirements defining the maximum level of credit supplied ($L^{max}_{b,t}$) and its maximum exposure to a single counterpart ($L^{max}_{b,f,t}$). These two regulatory constraints are defined as follows:

$$L^{max}_{b,t} = \frac{NW_{b,t}}{\gamma^B}\frac{1}{\omega^B}, \tag{45}$$

$$L^{max}_{b,f,t} = \kappa^B NW_{b,t}, \tag{46}$$

where $NW_{b,t}$ represents the bank's net worth, $\gamma^B \in (0,1)$ is the minimum capital adequacy ratio, ω^B is the risk-weight on corporate loans[27] and $\kappa^B > 0$.

Profits and bankruptcies The b-th bank's net worth evolves as follows:

$$NW_{b,t} = NW_{b,t-1} + (1-\tau^{tax}_t)\Pi_{b,t} - DIV_{b,t}, \tag{47}$$

where τ^{tax}_t is the tax rate, $\Pi_{b,t}$ are bank profits and $DIV_{b,t}$ are dividends (see (51)). Profits are defined as:

$$\Pi_{b,t} = \sum_{f=1}^{\eta^f} i_{b,f,t}L_{b,f,t} - \sum_{f\in\mathcal{D}^F} NPL_{b,f,t}, \tag{48}$$

where the first term on the right hand side is the sum of returns from solvent borrowers, while the second represents the total value of non-performing loans, with $\mathcal{D}^F$ being the set of bankrupted firms.

According to the regulatory framework, the equity of each bank ($NW_{b,t}$) must cover at least a fraction $1/\gamma^B$ of its risk-weighted assets $\omega^B L_{b,t}$, namely:

$$NW_{b,t} \geq \frac{\omega^B L_{b,t}}{\gamma^B}. \tag{49}$$

If condition (49) is satisfied, the bank computes a precautionary capital buffer on total deposits to face unexpected increases in future credit demand:

$$\Delta^D_{b,t} = \frac{\omega^B D_{b,t}}{\gamma^B} - NW_{b,t}, \tag{50}$$

and pays the net worth in excess as dividends to the owner:

$$DIV_{b,t} = \max\left(0, -\Delta^D_{b,t}\right). \tag{51}$$

[27] The underlying assumption is that the risk-weight on cash and government bonds is zero.

Conversely, when a bank does not meet the regulatory condition (49), the recapitalization and default procedure consists of the following steps. The bank b computes the minimum equity variation which satisfies (45):

$$\Delta^L_{b,t} = \frac{\omega^B L_{b,t}}{\gamma^B} - NW_{b,t}. \tag{52}$$

Then, if the required capital $\Delta^L_{b,t}$ is less than the banker's own financial wealth (i.e., deposits, $D^B_{b,t}$), the banker recapitalize the defaulted bank and the banks' net worth is updated as follows:

$$NW_{b,t} = NW_{b,t} + \Delta^{NW}_{b,t}, \tag{53}$$

with $\Delta^{NW}_{b,t}$ selected from:

$$\Delta^{NW}_{b,t} = \min\left[D^B_{b,t}, \max\left(\Delta^D_{b,t}, \Delta^L_{b,t}\right)\right]. \tag{54}$$

These resources reduce the banker's own deposits and income accordingly:

$$D^B_{b,t} = D^B_{b,t} - \Delta^{NW}_{b,t}, \tag{55}$$

$$Y_{b,t} = Y_{b,t} - \Delta^{NW}_{b,t}. \tag{56}$$

If the banker does not have sufficient financial resources to recapitalize the bank (i.e., $\Delta^L_{b,t} \geq D^B_{b,t}$), the latter is declared bankrupt. In this case the bank losses are borne by the government which provides public liquidity to recapitalize default bank[28] restoring its full functionality, namely:

$$EXP_t = EXP_t + \Delta^G_{b,t} = EXP_t + \frac{\omega^B D_{b,t}}{\gamma^B} - D^B_{b,t} - NW_{b,t}. \tag{57}$$

where EXP_t is the public liquidity provided to recapitalize default banks. The bank's net worth as well as the banker's income and deposits are updated as follows:

$$NW_{b,t} = \Delta^G_{b,t} + NW_{b,t} + D^B_{b,t}, \tag{58}$$

$$Y_{b,t} = Y_{b,t} - D^B_{b,t}, \tag{59}$$

$$D^B_{b,t} = 0. \tag{60}$$

Finally, a bank which has received public support will use future dividends (see (51)) to buy back the additional shares issued for the bailout to the government ($\Delta^G_{b,t}$). Notice that the recapitalization and default procedure does not affect depositors because banks participate in a Deposit Guarantee Scheme (DGS) to protect households and firms from losses on deposits. Hence, the DGS acts as a safety net to avoid bank runs following the illiquidity of financial institutions.[29]

A.6. Initialization

We initialize the system at the steady-state under the following assumptions:

[28] Since we introduce the government after $t = 500$ periods, banks are bailed by the central bank through a variation in the monetary base before that moment, namely: $M_t = M_{t-1} + \Delta^G_{b,t}$ if $t < 500$.

[29] Deposits insurance is in force in Europe since the Directive 2014/49/EU.

1. All markets clear:[30]

$$\begin{aligned} \text{labour market:} \quad & n^W && = n^E \Delta X^d_{N,E} && + n^C \Delta X^d_{N,C} && + n^K \Delta X^d_{N,K}, && (62) \\ \text{energy market:} \quad & n^E Q_E && = && n^C \Delta X^d_{E,C} && + n^K \Delta X^d_{E,K}, && (63) \\ \text{capital market:} \quad & n^K Q_K && = n^E \Delta X^d_{K,E} && + n^C \Delta X^d_{K,C}, && && (64) \\ \text{fossil fuel market:} \quad & Q_O && = n^E \Delta X^d_{O,E}. && && && (65) \end{aligned}$$

2. All firms set their price to maximize profits and operate under perfect competition, namely:

$$\Pi_f = 0. \tag{66}$$

3. Fossil fuel expenditure over total final consumption is equal to $\nu^O = 0.023$:

$$P_O Q_O = \nu^O n_C P_C Q_C. \tag{67}$$

4. Firms' deposits and loans are equal to total revenues:

$$D_f = L_f = P_f Q_f. \tag{68}$$

5. The initial wage is set $W_0 = 10$ as a numerator.

[30]We remove the equilibrium condition on the consumption market:

$$n^E \Pi_E + n^C \Pi_C + n^K \Pi_K + n^W W + P_O Q_O = n^C P_C Q_C, \tag{61}$$

since it is redundant by Walras's law.

B. Model calibration and validation

Since the focus of the work is on the European economy, we set the parameters of the model to reproduce the empirical regularities observed in that area. In particular, we follow a procedure similar to Ciola et al. (2022b) to set the values of the parameters and then compare the simulated time series with the quarterly macroeconomic data of the (Euro) Area-wide Model (AWM) database (Fagan et al., 2005). In this appendix, we show the calibration results, focusing on the definition of the area-specific parameters and the goodness of fit of the simulated time series to actual data.[31]

B.1. Parameters calibration

B.1.1 Workers and discount factors

We set the number of workers ($n^W = 1,000$) to ensure sufficient interactions in the simulated economy and allow the emergence of endogenous dynamics from the decentralized behaviour of the heterogeneous agents. At the same time, we estimate the parameters governing the wage equation on EA quarterly time series between 1970-Q1 and 2017-Q4 (see Appendix B.3). Our results indicate a moderate persistence in wages ($\hat{\rho}^W = 0.56$), with insiders having approximately the same bargaining power of outsiders ($\hat{\theta}^W = 0.51$). At the same time, observed inflation plays a fundamental role in anchoring expectations ($\hat{\iota}^W = 0.67$).

We assume, as in standard consumption capital asset pricing models (see Cochrane, 2009), the long-term relationship between households and firms' discount factors (β^C and β^F, respectively) and asset returns:

$$\beta^C = \left(1 + \mathbb{E}\left[r_t^{RF}\right]\right)^{-1} \quad \text{and} \quad \beta^F = \left(1 + \mathbb{E}\left[r_t^{E}\right]\right)^{-1}, \tag{69}$$

where ($\mathbb{E}[r_t^{RF}] = 0.4\%$) is the average quarterly real risk-free rate in the EA between 1970-Q1 and 2017-Q4, and ($\mathbb{E}[r_t^E] = 2.0\%$) is the real quarterly return on risky assets from 2002-Q1 to 2021-Q4, computed as the inflation-adjusted ratio between the gross operating surplus of firms and the households' non-financial and financial wealth (source: ECB Statistical Data Warehouse).

B.1.2 Firms

Following the findings of van der Werf (2008), we set the same elasticity of substitution in consumption, capital and energy sectors ($\sigma_C = \sigma_E = \sigma_K = 0.5$). At the same time, we estimate the depreciation rate of capital from the ratio between the current-cost depreciation of fixed assets and the net capital stock in the EA from 1995 to 2020, finding an average annual value of 5% ($\delta_K = 0.05/4$, source: AMECO database). On the contrary, we assume for simplicity that the other production inputs (i.e., energy, labour and fossil fuel) and the consumption good fully depreciate in the current period ($\delta_E = \delta_N = \delta_O = \delta_C = 1$).[32]

We use the symmetric input-output tables at basic prices of Eurostat to estimate the factor shares of sectoral production functions. The database contains the annual nominal value of intermediate goods transactions, labour cost, final consumption expenditure and investments in the EA from 2010 to 2019. We divide the 65 main activities of the dataset (European Classification of Economic Activities – NACE Rev. 2) between consumption and capital sectors according to the weight of final

[31] We refer the interested reader to Ciola et al. (2022b) for the remaining parameters regarding the matching protocol and the credit market.

[32] This assumption does not change the network of existing market relationships but reflects that, for example, firms cannot use past or future workers' time in current production.

consumption expenditure and investments on total demand. Conversely, we define the energy sector with the categories "Electricity, gas, steam and air conditioning" and "Coke and refined petroleum products" already contained in the original tables.

We compute the sectoral factor shares by dividing the nominal expenditure on intermediate inputs (i.e., the capital in our framework), labour and energy by total sectoral costs (see Table 4). Further, we use the energy sector's consumption of "Mining and quarrying" goods (which contains "Mining of coal and lignite" and "Extraction of crude petroleum and natural gas") to calculate the weight of fossil fuels in energy production. Moreover, we use the share of imports to identify the dependence on foreign inputs (i.e., 89% in 2019, which implies $\eta^O = 0.11$). Overall, labour is the main production factor in consumption and capital sectors, while fossil fuels cover the majority of costs in energy firms (see Table 4). Unsurprisingly, energy services, while necessary, participate only marginally in production (Kilian, 2008).

Similarly, we use the sectoral classification described above to arrange the latest annual enterprise statistics produced by Eurostat (arranged in 65 main activities according to NACE Rev. 2) in consumption, capital and energy enterprises. We assume an adequate number of consumption firms ($\mathcal{N}^C = 100$) to allow sufficient interactions between agents and set the rest of the firms' population proportionally to the actual shares observed in the EA (see Table 4). As a result, the consumption sector covers the majority of firms, followed by capital ($\mathcal{N}^K = 60$) and energy ($\mathcal{N}^E = 15$) enterprises and banks ($\mathcal{N}^B = 10$).

Table 4: *CES production function parameters.*

		Consumption (C)	Capital (K)	Energy (E)
Number of firms	$\mathcal{N}^f$	100	60	15
Capital share	$A_{K,f}$	0.25		0.18
Labour share	$A_{N,f}$	0.70	0.94	0.18
Energy share	$A_{E,f}$	0.05	0.06	0.64*
Elasticity of substitution	σ_f	0.50	0.50	0.50

*: share of fossil fuels in energy production, of which 91% imported from abroad in 2019.

Lastly, since there is no public-available data on the parameters governing the adjustment process of prices and desired quantities, we fix their values to ensure sufficient persistence in firms' behaviour ($\zeta^Q = \zeta^P = 0.75$), avoid excessive volatility in the system ($\gamma^{PQ} = 0.05$) and minimize the distance between simulated and actual time series (see the next section). Further, we choose a relatively high intensity of choice ($\omega = 10$) to reproduce the observed heterogeneity in firms' dimensions (see, among others, Okuyama et al., 1999; Ramsden and Kiss-Haypál, 2000; Axtell, 2001; Gaffeo et al., 2003).

B.1.3 Public sector

The central bank adjusts the risk-free interest rate using an inertial Taylor rule (12). We set the quarterly inflation rate target ($p^* = 0.02/4$) following the existing literature (Taylor, 1993; Taylor and Williams, 2010) and the medium-term objective chosen by the European Central Bank. At the same time, we compute the target unemployment rate as the median value observed in the EA between 1970 and 2017 ($u^* = 0.087$). Lastly, we rely on the empirical analysis of Smets and Wouters (2005) to determine the remaining parameters of the rule ($\rho^{CB} = 0.85; \lambda^u = 0.11; \lambda^p = 1.41$).

We use the estimates of Ciola et al. (2022b) to set the target debt to GDP ratio ($b^* = 0.75$) and the adjustment coefficient of public finances ($\rho^G = 0.007$). Conversely, we calculate the average social expenditure (net of pension transfers and contributions) over GDP in the EA between 1995 and 2020 to set the relative value in the model ($\psi^G = 0.095$, source: Eurostat).

B.2. Goodness of fit of the model

We conclude this appendix by evaluating the goddesses of fit of the model to the EA data. We divide the analysis between dynamic (i.e., business cycle) and cross-sectional properties of the simulated time series.

Business cycle The latest version of the Area-wide Model (AWM) database (Fagan et al., 2005) provides a broad range of quarterly time series on the EA economy between 1970-Q1 and 2017-Q4. Therefore, we choose this dataset as a benchmark to validate our model on real-world data.

We simulate $1,000$ independent replicas of the model starting from different random seeds and compute the averages plus the 90% bootstrap confidence intervals of selected statistics. The time series included in the analysis are the logarithms of real gross domestic product (GDP), gross fixed capital formation, consumption (CPI) and energy (EPI) price indexes, the unemployment rate and the risk-free interest rate. Since the focus of the work is on the response of the economy to energy shocks, we validate our simulations on the short and medium-term properties of real-world business cycles. Accordingly, we extract the cyclical component of actual and simulated time series through the Hodrick–Prescott filter (Hodrick and Prescott, 1997).

Starting from business cycle volatility, the standard deviations of the simulated time series properly track the values observed in EA data (Table 5). As expected, fluctuations in real investments are ampler than in aggregate production, even if the model overestimates their size. On the contrary, energy prices are more stable than the observed time series. This result emerges from the simplifying assumption of a constant relative price of fossil fuels in the model.[33] Indeed, in the real world, the latter depends more on global than on local factors and is subject to wide fluctuations (Kilian, 2008; Baumeister and Kilian, 2016). As a result, energy prices, which depend heavily on this production input (see Table 4), are less volatile in our model than in real-world data.

Table 5: *Standard deviation of filtered time series.*

	EA data	Simulations		
		Mean	90% C.I.	
Real GDP	0.011	0.014	0.012	0.015
Real investment	0.027	0.130	0.117	0.148
Unemployment rate	0.004	0.012	0.011	0.013
CPI	0.010	0.017	0.015	0.019
EPI	0.041	0.017	0.015	0.019
Policy rate	0.003	0.002	0.002	0.003

Note: mean and 90% confidence intervals of simulated data calculated on $1,000$ independent replicas.

Moving to the dynamical properties of the model, the empirical time series show a positive autocorrelation in the short run, which reverses in the medium term (Figure 11a). The data generated by the model reflect this behaviour, even though real investments and the unemployment rate display a lower persistence in the short term, while consumer and energy prices overestimate the medium-run negative correlation. Similarly, the crosscorrelations of the simulated time series

[33] We must rely on this assumption since the focus of the work is on the effects of an exogenous increase in the price of fossil fuels, and we must control its value. Adding a stochastic fossil fuel price would simply increase the complexity of the analysis without providing further insights.

with aggregate production follow real-world observations (Figure 11b). However, the model fails to accurately reproduce the dynamic relationships between real GDP, investments, energy prices and the central bank policy rate. Nevertheless, even if their size is not correct, the sign of those correlations is in line with real-world data.

Cross-sectional regularities Having established the capability of our framework to reproduce the dynamics of the EA business cycle, we illustrate supplementary results produced by the model that replicate other aspects of real-world economies. To improve the robustness of our analysis, we focus only on the last observation of each independent replica, thus allowing us to investigate the unconditional behaviour of the simulated time series.

First, our theoretical framework can generate two common empirical regularities, namely the Philips curve and the Okun's law (see Figure 12). In particular, the model can reproduce, even without assuming it, the inverse relationship of inflation and real GDP with the unemployment rate. Moreover, the Philips curve follows recent developments in its shape, with lower responsiveness of inflation to changes in the unemployment rate than in the past (see Negro et al., 2020, for an empirical analysis and a discussion on the causes of that shift). On the contrary, the elasticity of unemployment with real GDP (-0.40) is in line with recent estimates of its value in EA countries (ECB, 2011).

Second, a prominent feature of our model is the introduction of heterogeneous interacting agents. Accordingly, that allows us to assess the distributional properties of the simulated economy (Figure 13). The Gini index computed on disposable income slightly overestimates the average level observed in the EA (0.39 against 0.30). Nevertheless, the distributive effects of government transfers replicate the real-world values, with a reduction of 14 and 11 percentage points in simulated and EA data, respectively (OECD, 2008). Moreover, the Gini index increases with unemployment (Parker, 1998), as shown in the right pane of Figure 13. In other words, inequality follows business cycle fluctuations, reaching its maximum level during recessions.

Lastly, since the energy sector plays a fundamental role in our model, we analyse its unconditional behaviour (Figure 14). As expected, the demand for energy increases with aggregate production with an estimated elasticity of 73%, in line with the empirical results of Burke and Csereklyei (2016). Moreover, the aggregate expenditure on fossil fuels over nominal GDP fluctuates around the 2.3% average value observed in the EA between 2016 and 2020 (Figure 14, right pane).

B.3. Estimation of the wage equation

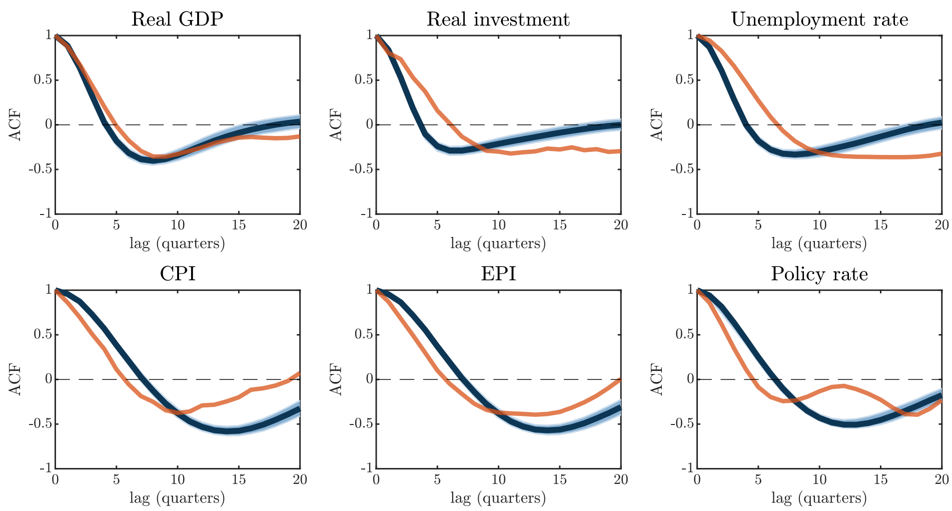
We conclude this appendix by describing the procedure we follow to estimate the parameters of the wage equation ((29) and (30)) on EA quarterly time series between 1970-Q1 and 2017-Q4 (data source: AWM database, see Fagan et al., 2005). A natural way to infer the required values would be to estimate the empirical model:

$$w_t = \beta_0 + \beta_1 z_{t-1} + \beta_2 U_{t-1} + \beta_3 p_{t-1} + e_t \tag{70}$$

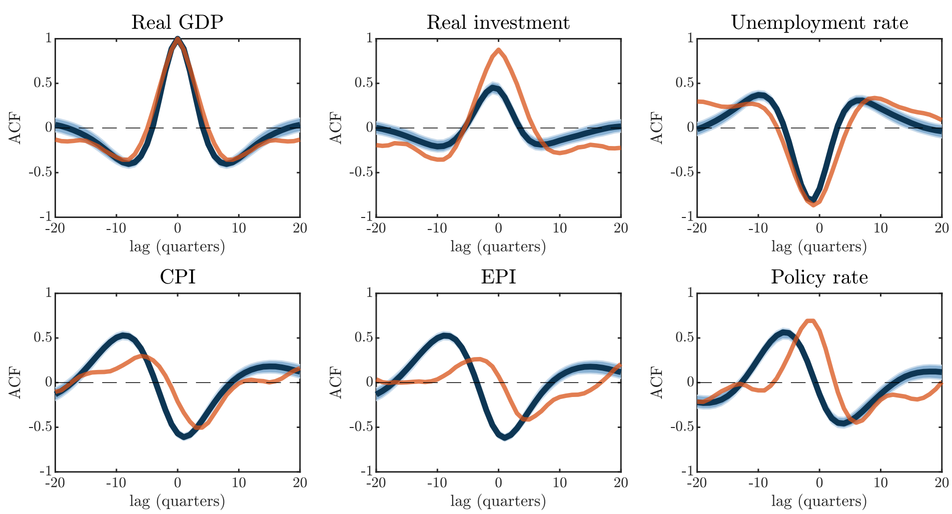
where w_t and z_{t-1} are the growth rates of the nominal wage per worker and labour productivity (measured as the ratio between real GDP and total employment), U_{t-1} is the unemployment rate and p_{t-1} the consumer price index inflation. Nevertheless, the time series are not stationary except for labour productivity.[34] Accordingly, we estimate the following Error Correction Model (ECM):

$$\Delta w_t = \beta_0 + \beta_1 w_{t-1} + \beta_2 z_{t-2} + \beta_3 U_{t-2} + \beta_4 p_{t-2} + \beta_5 \Delta w_{t-1} + \beta_6 \Delta z_{t-1} + \beta_7 \Delta U_{t-1} + \beta_8 \Delta p_{t-1} + e_t \tag{71}$$

[34] The Augmented Dickey-Fuller test on nominal wage growth, unemployment and inflation rates does not reject the null hypothesis of unit root at 10% level of significance with a p-value of 0.4561, 0.1169 and 0.5788, respectively.



(a) *Time series autocorrelation*



(b) *Time series cross-correlation with real aggregate production.*

Figure 11: *Autocorrelation and cross-correlation structures of main aggregate variables: simulated against empirical data.*

Note: auto- and cross-correlation functions of simulated (blue error bars) and US time series (red lines). Median and 90% confidence intervals of simulated data calculated on $1,000$ independent replicas.

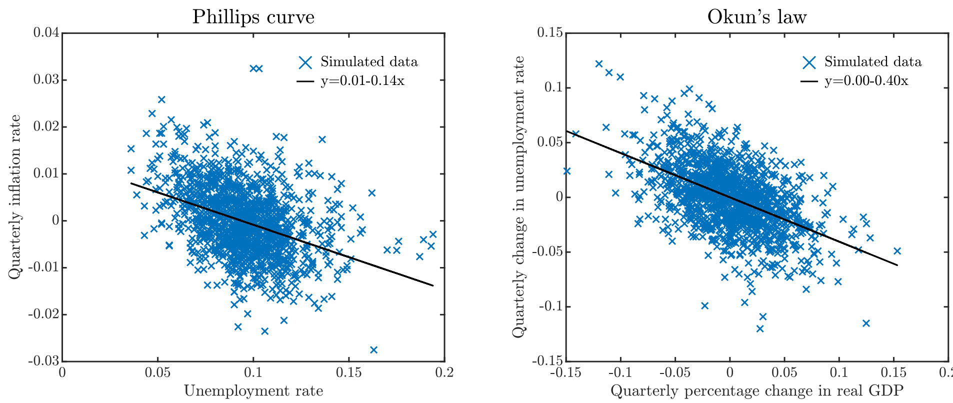


Figure 12: *Phillips curves and Okun's law.*

Note: quarterly inflation rate (left pane) and real GDP growth rate (right pane) against unemployment rate. Results calculated on the last observations of $1,000$ independent replicas.

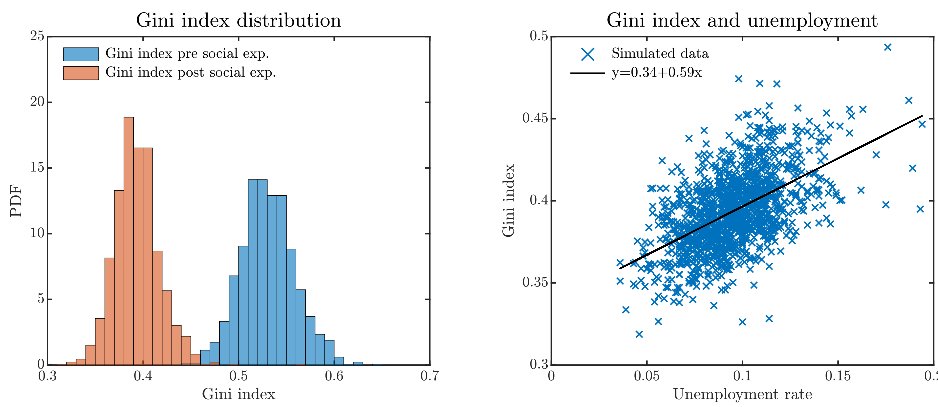


Figure 13: *Gini index and business cycle.*

Note: Gini index before and after public social expenditure (left pane) and for different levels of unemployment (right pane). Results calculated on the last observations of $1,000$ independent replicas.

where Δ identifies the first difference of a variable and we add one lag of the dependent variable to control for residuals autocorrelation.

We conclude by rewriting (29) and (30) in terms of nominal wage growth rate:

$$w_t = \rho^W + (1-\rho^W)\left[\theta^W(1+z_{t-1}) + (1-\theta^W)(1-U_{t-1})\right] + \iota^W p_{t-1} + (1-\iota^W)p^* \tag{72}$$

where we substitute the relative demand for labour N^d_{t-1}/N^{emp}_{t-1} with the gross growth rate of labour productivity $1+z_{t-1}$ because of the lack of empirical data. In other words, we overcome the problem of insufficient observations by assuming that the growth rate of labour productivity can be used as a proxy for the bargaining power of insiders. Indeed, they would capture all the increase in labour productivity if they had complete control over wage negotiations. Lastly, we calculate the unconditional estimators of the parameters from (71) and (72):

$$\hat{\theta}^W = \frac{\hat{\beta}_2/\hat{\beta}_1}{\hat{\beta}_2/\hat{\beta}_1 - \hat{\beta}_3/\hat{\beta}_1} = \frac{\hat{\beta}_2}{\hat{\beta}_2 - \hat{\beta}_3},\ \hat{\rho}^W = 1 - \frac{\hat{\beta}_3 - \hat{\beta}_2}{\hat{\beta}_1} \text{ and } \hat{\iota}^W = -\frac{\hat{\beta}_4}{\hat{\beta}_1}. \tag{73}$$

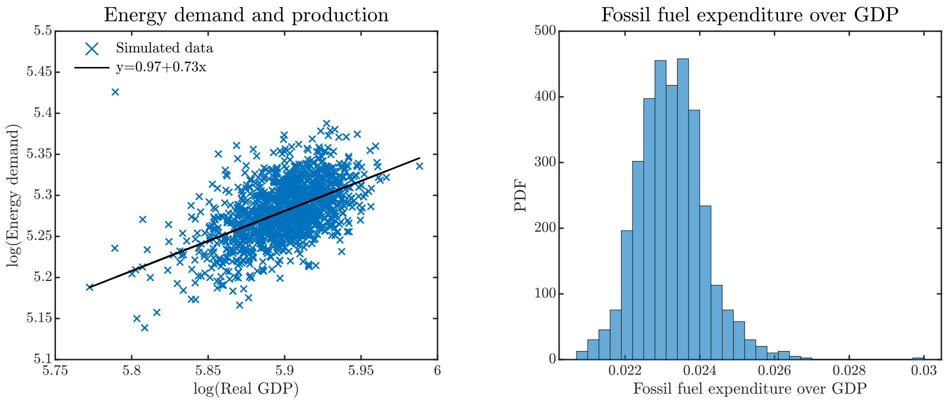


Figure 14: *Aggregate production and energy demand.*

Note: Unconditional (long-term) relationship between energy demand and aggregate production (left pane). Simulated distribution of fossil fuel expenditure over GDP (right pane). Results calculated on the last observations of 1,000 independent replicas.

Table 6 shows the results of the estimation, which indicate a moderate persistence in wages ($\hat{\rho}^W = 0.56$), with insiders having approximately the same bargaining power of outsiders ($\hat{\theta}^W = 0.51$). Lastly, observed inflation plays a fundamental role in anchoring expectations ($\hat{\iota}^W = 0.67$).

Table 6: *Wage equation.*

OLS, using observations 1971:3–2017:4 ($T = 186$).
Dependent variable: Δw_t.

	Coefficient	Std. Error	t-ratio	p-value
const	0.0155	0.0032	4.792	0.0000
w_{t-1}	−0.6473	0.0942	−6.871	0.0000
z_{t-2}	0.1464	0.0974	1.504	0.1344
U_{t-2}	−0.1382	0.0286	−4.834	0.0000
p_{t-2}	0.4331	0.0905	4.785	0.0000
Δw_{t-1}	−0.3133	0.0695	−4.511	0.0000
Δz_{t-1}	−0.1859	0.0722	−2.576	0.0108
ΔU_{t-1}	−0.3732	0.2032	−1.836	0.0679
Δp_{t-1}	0.2322	0.0658	3.532	0.0005

Mean dependent var	−0.0002	S.D. dependent var	0.0064
Sum squared resid	0.0039	S.E. of regression	0.0046
R^2	0.5007	Adjusted R^2	0.4785
$F(8, 180)$	22.5622	P-value(F)	0.0000

C. Model parameters

#	Description	Name	Value
1	Number of workers	$\mathcal{n}^W$	1000
2	Discount rate households	β^C	0.996
3	Memory parameter	ε	β^C
4	Marginal propensity to consume out of wealth	χ	$1-\beta^C$
5	Discount rate firms	β^F	0.980
6	Dividend payout ratio firms	μ^F	$1-\beta^F$
7	Wage stickiness	ρ^W	0.56
8	Insider-outsider bargaining power	θ^W	0.51
9	Inflation anchoring	ι^W	0.67
10	Labour depreciation	δ_N	1
11	Number of C-firms	$\mathcal{n}^C$	100
12	Factor share capital (C-firms)	$A_{N,C}$	0.25
13	Factor share labour (C-firms)	$A_{K,C}$	0.70
14	Factor share energy (C-firms)	$A_{E,C}$	0.05
15	Depreciation rate of consumption goods	δ_C	1
16	Elasticity of substitution (C-firms)	σ_C	0.50
17	Number of E-firms	$\mathcal{n}^E$	100
18	Factor share capital (E-firms)	$A_{N,E}$	0.18
19	Factor share labour (E-firms)	$A_{K,E}$	0.18
20	Factor share natural resource (E-firms)	$A_{O,E}$	0.64
21	Depreciation rate of energy services	δ_E	1
22	Elasticity of substitution (E-firms)	σ_E	0.50
23	Number of K-firms	$\mathcal{n}^K$	60
24	Factor share labour (K-firms)	$A_{N,K}$	0.94
25	Factor share energy (K-firms)	$A_{E,K}$	0.06
26	Depreciation rate of physical capital	δ_K	0.05/4
27	Elasticity of substitution (K-firms)	σ_K	0.50
28	Size of exploration	γ^{PQ}	0.05
29	Speed of adjustment: quantity	ζ^Q	0.75
30	Speed of adjustment: price	ζ^P	0.75
31	Intensity of choice	ω	10
32	Foreign natural resource expenditure over GDP	ν^O	0.023
33	Depreciation rate of foreign natural resource	δ_O	1.00
34	Share of foreign natural resource going to E-firms	η^O	0.09
35	Number of banks	$\mathcal{n}^B$	10
36	Capital adequacy ratio	γ^B	0.08
37	Risk weighting	ω^B	1
38	Maximum single exposure to borrowers	κ^B	0.25
39	Interest rate setting parameter	ϱ^B	0.029/4
40	Interest rate setting parameter	ρ^B	0.017/4
41	Interest rate setting parameter	ι^B	0.001/4
42	Share of loans repaid at each time-step	θ^B	0.0125
43	Number of entrepreneurs	$\mathcal{n}^F$	$\mathcal{n}^C+\mathcal{n}^E+\mathcal{n}^K+\mathcal{n}^B$
44	Number of consumers	$\mathcal{n}^H$	$\mathcal{n}^W+\mathcal{n}^F$
45	Inflation target	p^*	0.02/4
46	Target unemployment rate	u^*	0.087
47	Steady state real interest rate	r^*	$1/\beta^C-1$
48	Monetary policy rule weights: inflation	λ^p	1.41
49	Monetary policy rule weights: unemployment	λ^u	0.11
50	Speed of adjustment of the monetary policy rule	ρ^{CB}	0.85
51	Target debt-GDP ratio	b^*	0.75
52	Speed of adjustment to target debt-GDP ratio	ρ^G	0.007
53	Share of social expenditures	ψ^G	0.094
54	Maximum number of new partners (C-market)	$\mathcal{Z}^C$	0.25
55	Maximum number of new partners (E-market)	$\mathcal{Z}^E$	4
56	Maximum number of new partners (K-market)	$\mathcal{Z}^K$	4
57	Maximum number of new partners (labour market)	$\mathcal{Z}^N$	10
58	Maximum number of new partners (credit market)	$\mathcal{Z}^B$	0.20
	Initial wage rate	W_0	10
	Time length	T	5000
	Total number of non-composite parameters		52

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