Energy price shocks in the European Union: macroeconomic impacts, distributional effects and policy responses

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Abstract

The macroeconomic consequences of energy shocks, their distributional effects, and the potential remedies have recently scaled up the EU policy agenda. In this paper, we employ an agent-based, stock-flow consistent model empirically calibrated to the EU27 economy to evaluate the macroeconomic effects of an energy price shock akin to that which took place in 2022. Our focus is on a scenario in which the economy experiences a sudden, sharp increase in the price of imported fossil fuels, which affects the price of energy and thereby firms' production costs and output prices. We show that the magnitude and persistence of the resulting inflationary episode, as well as the effects on functional income distribution, employment and economic activity, strongly depend on government intervention, the sensitivity of nominal wage claims to inflation, and the extent to which increases (and subsequent decreases) in the price of energy inputs are passed on into final output prices. We find that an empirically calibrated mix of transfer payments can be very effective at mitigating the macroeconomic impacts of the energy price shock. However, such policy interventions are never able to fully countervail the shift toward profits of the income distribution. Additional measures targeting prices to ensure the complete pass-through of energy price decreases once the shock recedes provide a solution to this issue.

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1 Introduction

The global turmoil produced by the Russian invasion of Ukraine has reignited the debate on the economic effects of energy price shocks, with the public and academic focus quickly shifting towards a number of classic questions, ranging from how much inflation central banks should tolerate, to the feasibility of unconventional interventions such as energy price caps and windfall profit taxes on energy producers. There are, however, at least two elements of novelty in the current debate. First, the Ukraine-war shock, which had limited scope in space and time, occurs in a global economic environment undergoing the green transition, which may have significant impacts on the price of energy, especially through the widespread deployment of carbon pricing. Second, there appears to be an increasing awareness that cost-push shocks in general and energy price shocks in particular entail a distributional conflict regarding who will eventually bear the generated burden which also depend on institutional factors (Lavoie, 2024; Lorenzoni and Werning, 2023).

In this context, our work contributes to shed light on the macroeconomic effects of energy price shocks, with a particular focus on the effects of varying institutional settings and the evaluation of policy interventions aimed at reversing the distributional shifts implied by these shock. The geographical scope of our analysis is the EU27 economy, a large developed economic area lacking in domestic fossil fuel resources and hence highly exposed to a shock such as that induced by the war in Ukraine.

To perform our analysis, we extend the *Dystopian Schumpeter meeting Keynes* (DSK) macroeconomic agent-based model (Lamperti et al., 2018a, 2019, 2020, 2021).[1] The DSK model builds on Dosi et al. (2010, 2013, 2015, 2017b) and depicts an economy featuring endogenous growth and business cycles, enriched by an energy sector which supplies energy as a necessary input to firms' production. The model is empirically calibrated on the EU27 economy using the Simulated Method of Moments and additionally validated on a wide range of macroeconomic and microeconomic stylised facts (Reissl et al., 2024). We enrich the model with a fossil fuel sector and we study the impact of a temporary shock to the price of imported fossil fuels, which are needed as an input in the domestic production of energy. The sudden surge in the price of energy is a cost-push shock for producers of final output. We then analyse the economic consequences of this shock on GDP, employment, inflation, firms' bankruptcies and defaults and functional income distribution under diverse institutional settings and policy responses.

The reaction of firms is chiefly characterised by how they are able to pass the increase in energy cost through their output prices. We assume that different institutional settings lead to diverse levels of pass-through and asymmetries in the pass-through rates of energy price increases

[1] An overview on the DSK model and its key results is provided in Lamperti and Roventini (2022). A detailed presentation of the DSK model is provided in Reissl et al. (2024). For surverys on macroeconomic agent-based models, see Fagiolo and Roventini (2017); Dawid and Delli Gatti (2018); Haldane and Turrell (2019); Dosi and Roventini (2019).

and subsequent decreases. The reaction of households is strongly determined by the sensitivity of nominal wage developments to the inflation rate, which dictates the extent to which real wages decline as a consequence of the energy price shock. A high sensitivity allows for a better preservation of purchasing power, but it also gives rise to additional inflationary pressures if firms concurrently seek to protect their profit margins. Together, the behaviours of firms and households in response to the shock determine the outcome of the inflation conflict and which of the two bears the associated burden (Lavoie, 2024; Lorenzoni and Werning, 2023). Finally, we consider various constellations of potential government interventions in the form of transfer payments to firms and households, and price controls.

We find that in the absence of policy intervention and under empirically calibrated pass-through rates, the energy price shock causes a sizeable macroeconomic loss, a steep decline in the share of wages in total income, and a deterioration of firm balance sheets manifesting in increased default and bankruptcy rates. Inflation subsides following the economic recovery, but functional distribution shifts permanently in favour of the firm's profit share. A policy intervention consisting of transfer payments distributed between households and firms following empirical data on the EU 2022 policy mix is able to strongly mitigate the macroeconomic effects of the shock without producing substantially higher inflation rates, even in cases in which nominal wage claims are assumed to be very sensitive to the rate of inflation.

Additionally, we find that this empirically calibrated policy intervention, where transfer payments are heavily concentrated on households, delivers superior outcomes compared to alternatives that target payments more toward firms. However, we also observe that none of these policies can restore the functional distribution to its pre-shock levels. To achieve this, we show that additional measures targeting prices are necessary to ensure the complete pass-through of the decrease in energy prices to the final output price once the shock subsides.

The rest of the paper is organised as follows: section 2 reviews the existing literature on the macroeconomic effects of energy price shocks. Section 3 contains a compact description of the DSK model. Section 4 briefly discusses the calibration and validation procedure. Section 5 describes the scenarios we simulate, and section 6 presents the results. Finally, section 7 concludes.

2 Related literature

The paper primarily contributes to the economic literature on energy price shocks (see Kilian 2008 for a review), with a focus on the macroeconomic dimension, and in particular on real aggregate effects on GDP, inflation, and functional income distribution.

The early macro-energy literature was rooted in the neoclassical growth framework, in which energy is exclusively a factor of production without considering any impact on its final consumption (as does our model which we outline below). The main goal of such a literature was to try to interpret the severe economic downturns experienced amid the oil shocks of the 1970s. Contributions in this line of inquiry identify imperfect competition as the primary driver of rising markups, low output, and declining real wages in the aftermath of energy price shocks (Rotemberg and Woodford, 1996). They also highlight downward adjustments in capacity utilisation stemming from decreased capital productivity (Finn, 2000), and differences in short and long-run substitution elasticities of energy in the production function due to heterogeneous capital vintages with different energy efficiencies (Atkeson and Kehoe, 1999).

Contemporary macroeconomic literature has significantly enhanced the analysis adding to the supply-side framework pertinent demands-side impact channels for energy price shocks. Modern supply-side studies often utilise production network models and generally suggest negligible macroeconomic impacts from energy price shocks (Baqaee and Farhi, 2019; Bachmann et al., 2022). Furthermore, advancements in general equilibrium frameworks have stressed the importance of uncertainty surrounding energy price shocks, showing the potential efficiency of price controls as a response to energy crises (Krebs and Weber, 2024).

Recent advancements in the New Keynesian literature have integrated energy into the consumption function (Blanchard and Gali, 2007; Bodenstein et al., 2011). Typically, these studies find limited impacts of energy price shocks at the macroeconomic level, often due to households exhibiting pronounced consumption smoothing behaviour, whereby temporary losses of real income have minimal consequences. In this literature, the recessions that followed energy price shocks are for the most part attributed to concomitant shocks, such as aggressive monetary policy reactions (Bernanke et al., 1997; Leduc and Sill, 2004). These results may arise from limitations embedded in the representative agent framework. Indeed, using a Heterogeneous-Agent New Keynesian (HANK) framework, Auclert et al. (2023) show that for a realistically low elasticity of substitution between energy and domestic goods and a realistically large aggregate marginal propensity to consume, adverse energy price shocks cause income losses which exert a sizable negative effect on GDP. Moreover, HANK models also show that the burden of energy price shocks is unequally distributed across income classes, with low-income and unemployed individuals being more severely affected, (Pieroni, 2023; Gnocato, 2023), an insight which has also been confirmed empirically (Känzig, 2023).

Alternative approaches to macroeconomic modelling have also been applied to investigate the impacts of energy price shocks. Turco et al. (2023) examine the macroeconomic implications of energy price shocks and the corresponding policy responses in a macroeconomic agent-based model (MABM). Their findings reveal that stagflation follows an energy price surge, with unequal impacts across the income and wealth distributions. Workers bear a significant portion of the burden, while entrepreneurs in the energy sector enjoy rent-like benefits. van der Hoog and Deissenberg (2011) study the effects of a stylised energy price shock in the EURACE MABM, finding that transfer policies similar to those we model in the present paper are effective at addressing the macroeconomic fallout generated by the shocks. Canelli et al. (2024) develop a medium-scale empirical Stock-

Flow-Consistent (SFC) model to assess the effects of an energy price shock on the Italian economy. Echoing Blanchard and Gali (2007), they identify the monetary authority's potentially negative role in steering macroeconomic adjustment. In the best scenario, characterised by a soft landing, the central bank can mitigate inflation, albeit at the expense of restraining economic growth and a deterioration of Italian public finances. Conversely, in a hard landing scenario, Italy faces additional short-term risks, including economic recession and heightened unemployment levels. Lastly, Wildauer et al. (2023) construct a multi-sector, post-Keynesian macroeconomic model to investigate the determinants of distributive effects arising from energy price shocks, with a specific focus on wages and profits.

Our paper also contributes to the literature on conflict inflation, initially proposed by Rowthorn (1977, 2024), which claims that inflationary episodes stem from disputes over the distribution of national income among various claimants. While the theory of conflict inflation has long been a cornerstone of post-Keynesian inflation theory (Arestis and Sawyer 2005; Setterfield 2007; Lavoie 2024), it has more recently found integration into ABMs (Rolim and Marins, 2024) as well as neoclassical models (Lorenzoni and Werning, 2023). Importantly, the conflict inflation framework also provides the theoretical underpinning for the "seller's inflation" mechanism devised by Weber and Wasner (2023), which has featured prominently in the current debate around rising inflation. The work of Wildauer et al. (2023) lies at the intersection between energy price shocks and conflict inflation. Their study illustrates that increases in energy prices create an aspiration gap between expected and actual wages and profits, potentially culminating in inflation spirals. The distribution of bargaining power between workers and firms dictates who can maintain the desired income share and who bears the brunt of the shock's impact. Similarly, Stiglitz and Regmi (2023), argue that the main determinants of the recent surge in inflation are linked to "industry-specific problems [...] possibly exacerbated by market power and market manipulation," rather than the tightness of labour markets.

Our work also adds up to the literature that explores the relationship between inflation, rising markups, and profit shares. The findings on markups tend to be heterogenous across countries. In the United States, Andler and Kovner (2022) report that both profits and markups have increased alongside rising prices, while wages have remained stagnant. In France, Arquié and Thie (2023) observe temporary increases in markups during 2021-2022. Conversely, Manuel et al. (2024) document a decline in UK markups following energy shocks, and Colonna et al. (2023) find that markups in Germany and Italy remained stable despite higher profit shares. Overall, ECB President Lagarde and Chief Economist Lane attribute part of the current inflationary pressure in the European Union to rising profit margins (Lagarde, 2023; Lane, 2023). Regarding profit shares, Hahn (2023) finds that European corporations have offset rising non-labour costs by increasing prices. The OECD (OECD, 2023) confirms a similar trend in unit profits across advanced economies (see also Glover et al. (2023)), while the International Monetary Fund (Hansen et al., 2023) highlights a strong correlation between the inflation surge of 2022-2023 and increased import prices and domestic profits.

In addition to inflation, the functional distribution of income is also a key determinant of aggregate demand in both the post-Keynesian tradition (Bhaduri and Marglin, 1990; Lavoie and Stockhammer, 2013, see e.g.) and the MABM one (Dosi et al., 2013, 2015, 2018; Caiani et al., 2019; Terranova and Turco, 2022; Fierro et al., 2023). A large empirical literature (e.g. Onaran and Galanis, 2013; Onaran and Obst, 2015) finds a positive relationship between the share of wages in national income and economic activity in many countries and regions, which are therefore classified as 'wage-led'. A similar channel also exists in the model which we employ, and indeed we find that a persistent change in functional distribution away from wage income as a consequence of an energy price shock gives rise to a slower post-shock recovery.

3 The DSK-SFC model

The present section provides a compact overview of the DSK model (Lamperti et al., 2018a, 2019, 2020, 2021) in its fully stock flow consistent version (Reissl et al., 2024), which we extend by including a fossil fuel sector and quantitatively calibrate on the European Union business cycles and growth rates. A more detailed description, including the balance sheet and transaction flow matrices, is provided in Appendix C. As its direct antecedent (Dosi et al., 2010), the DSK model couples a Schumpeterian engine of innovation-fuelled technological change in the manufacturing and energy sector with a Keynesian engine of demand generation and propagation. It comprises heterogeneous consumption and capital good firms (C-Firms and K-Firms hereafter). Both K-Firms and C-Firms employ energy to produce their output, which they purchase from an aggregated energy sector operating both 'green' and 'brown' plants, with the latter requiring a costly fossil fuel input supplied by a fossil fuel sector. Heterogeneous banks provide loans to C-Firms to finance their production and investment. The aggregate household sector purchases consumption goods and earns labour and dividend income. Finally, the model also contains a central bank and a government which conduct monetary and fiscal policy respectively.

3.1 Households

The aggregate household sector receives wage income from supplying labour to firms and the energy sector. In addition, it receives dividend payments from firms, the energy sector, banks and the fossil fuel sector. Finally, unemployed households receive unemployment benefits corresponding to a fraction of the market wage. Households cannot borrow and any savings are held in the form of bank deposits.

Households' desired nominal consumption expenditure is given by

$$C_{d,t} = \alpha_1(W_t + UB_t) + \alpha_2(Div_{t-1}) + \alpha_3 D_{h,t-1} \tag{1}$$

where W_t is wage income, UB_t are unemployment benefits, Div_{t-1} is dividend income from firms, banks, as well as the energy and fossil fuel sectors, and $D_{h,t-1}$ are accumulated bank deposits. If income is not sufficient to finance the desired consumption, household can rely on their stock of deposits.

Households supply any amount of labour demanded at the current nominal wage w_t, up to the current aggregate labour force, LS_t, which changes at the exogenous rate g_L. The nominal wage is uniform for all units of labour employed and changes according to:

$$\begin{aligned} w_{t+1} &= (1+\mathfrak{w}_t)w_t \\ \mathfrak{w}_t &= min(\overline{\mathfrak{w}}, max(-\overline{\mathfrak{w}}, \pi^* + \psi_1\widehat{\pi}_t + \psi_2\widehat{Pr}_t - \psi_3\widehat{U}_t)) \end{aligned} \tag{2}$$

where $\overline{\mathfrak{w}}$ is a bound on the absolute percentage change in the wage rate per period, π^* is the central bank's inflation target, $\widehat{\pi}_t$ is the deviation of current inflation from that target, $\widehat{Pr}_t$ is a weighted average of past changes in average labour productivity across firms, and $\widehat{U}_t$ is the change in the unemployment rate relative to the previous period.

3.2 Capital good firms

The $N1$ capital good firms demand labour and energy to produce a unique capital good with specific characteristics using an individual Leontief production technique. Machine tools are produced on demand when K-Firms receive orders from C-Firms and are delivered in the following period. Given its current individual production technique, every K-Firm k has an individual labour productivity, energy efficiency and emission intensity giving rise to labour and energy demand as well as emissions when producing capital goods. Prices for capital goods are set as a uniform markup over individual unit cost.

Both the production technology used by K-Firms and the characteristics of the offered capital goods change endogenously as a result of R&D. K-Firms are assumed to spend a fixed fraction of their revenue on R&D activities, which are carried out by hiring labour. Total R&D inputs are in turn divided between efforts directed toward innovation and efforts aimed at imitation of competitors' technologies. As in the original K+S models upon which the DSK model is based (e.g. Dosi et al., 2010), technological innovation and imitation are modelled as two-step stochastic processes as described in Appendix C.

The capital good market is characterised by imperfect information. Each K-Firm k competes for customers by sending brochures to randomly drawn C-Firms, informing the latter about the characteristics of the vintage of capital good currently offered by k, as well as the price charged by k. In every period, each C-Firm compares all the brochures it has received and chooses the most convenient supplier of capital goods, taking into account both the purchase price of capital goods and the unit cost of production resulting from using these capital goods in the production of consumption goods.

If K-Firm profits from the sale of capital goods are positive, they are taxed at a flat rate and a fixed share of after-tax profit is paid to households as a dividend. If a K-Firm loses all its customers or is unable to meet a payment obligation, it exits the market and is replaced by a new firm.

3.3 Consumption good firms

The consumption goods sector consists of $N2$ individual firms (C-Firms) which produces a homogeneous consumption good using labour, capital and energy. Since each C-Firm's capital stock is composed of a diverse set of capital vintages, typically from different suppliers, C-Firms differ in terms of technology, labour productivity, energy efficiency and emission intensity.

C-Firms' desired production is based on expected demand, which follows an adaptive expectation rule, but may be scaled back if the firm's existing capital stock is insufficient to carry out the planned production.[2] C-Firms can expand their productive capacity to satisfy their expected demand by investing in additional capital goods. In particular, C-Firms have a fixed and homogeneous target capacity utilisation (u) and the planned expansion investment is the difference between the desired and the current capital stock (net of depreciation). C-Firms may also replace technologically obsolete capital goods if the vintage offered by their current capital goods supplier is sufficiently superior. Each C-Firm chooses its supplier of capital goods by comparing the brochures received from K-Firms and calculating an attractiveness measure as detailed in Appendix C.

Each C-Firm sets a price for its output by applying a markup on its unit cost of production. The mark-ups are heterogeneous and change as a function of C-Firm market shares. Unit costs are also heterogeneous since they depend on the composition of the capital stock used in the production of each firm, which determines each firm's effective labour productivity, energy efficiency and emission intensity and hence the amount of labour and energy input demanded. Note that since the mark-up is applied to current unit cost, all changes in unit cost (e.g., through changes in the wage rate or the price of energy) are in the baseline setting fully and immediately passed through into the final selling price. The simulation experiments below (Section 5) explore the implications of partial pass-through in the case of energy price shocks.

C-Firm production and investment are financed through retained earnings (bank deposits) and loans from the banking sector. The maximum amount of credit a C-Firm can obtain is a multiple of its previous net revenues (sales revenue minus cost of inputs). Firms scale back their planned investment if the desired investment exceeds the amount that can be financed using retained earnings and the credit. In this case, the financially-constrained firm first cut the planned investment and, if this is not sufficient, also planned production.

The aggregate demand for consumption goods of the household sector is distributed to C-Firms

[2] The results of the model are typically robust for different expectation formation rules, see Dosi et al. (2020).

following a quasi-replicator dynamic (cf. Dosi et al., 2010), where the market share of each firm is a function of its competitiveness, $E_{c,t}$. Competitiveness is calculated usin the firm's selling price relative to the average across C-Firms $\left(\frac{p_{c,t}}{\widehat{p}_t}\right)$ and its relative ability to satisfy the demand received in the previous period.

C-Firms pay taxes at flat rate on profits. In addition, a fixed share of positive post-tax profits are distributed as dividends to households. A C-Firm fails if it cannot make a due payment, is unable to roll over its outstanding loans, if its net worth becomes negative, or if its market share falls below a small lower threshold. As in the case of K-Firms, all failing C-Firms are replaced one for one by new firms.

3.4 Banks

The banking sector consists of NB individual banks which are functionally identical, but differ in terms of the number of individual firm customers. To align with the empirical evidence (see, e.g. Berger et al., 1995; Ennis, 2001), at the beginning of a simulation, each bank is assigned a number of K-Firm and C-Firm customers drawn from a truncated Pareto distribution. Subsequently, the firm-bank network remains static. If a firm which is a customer of bank b fails, the new firm replacing it is assigned to the same bank. The aggregate deposits of households and the energy sector are distributed across all banks according to the number of firm customers of each bank.

Banks' main liabilities are deposits of firms, households and the energy sector. In the calibration shown in this paper, these deposits are not remunerated. On the asset side, banks lend to C-Firms. According to Basel-like macroprudential regulation, each bank can extend its credit up to a fixed multiple of its net worth. This implies a fixed target capital adequacy ratio in which loans receive a risk weight of one and other assets have a zero weight. Banks then rank their C-Firm customers following their debt service to revenue ratio, with the loan interest rate charged by bank b to C-Firm c being given by:

$$r^l_{b,c,t} = r^l_{b,t} + \left(rank_{c,t} - 1\right)\mathfrak{M}, \tag{3}$$

where $r^l_{b,t}$ is the base loan rate given by a constant and homogeneous mark-up over the central bank lending rate, $\mathfrak{M}$ is a parameter, and $rank_{c,t}$ is the quartile of the distribution of debt service-to-revenue ratios among b's customers to which c belongs. In addition, this ranking is also used to allocate credit when total credit demanded from b is larger than the maximum amount it is prepared to lend, with firms being served in ascending order of their debt service to revenue ratio. In addition to lending to C-Firms, banks purchase government bonds, with the demand for government bonds of each bank being a fixed fraction of its stock of firm loans. Banks use central bank reserves to make interbank payments, which they can borrow without limit at the central bank's lending rate. For simplicity, we do not depict an interbank market for reserves.[3]

[3]See Pallante et al. (2024) for an extension of the DSK model accounting for an interbank market.

Bank profits are calculated using all interest income and expenditures alongside any losses from defaults on C-Firm loans. If these profits are positive, banks pay a fixed share of them in taxes and then distribute a fixed share of post-tax profits as dividends to households.

If an individual bank's net worth becomes negative it fails. In the present paper, it is assumed that failed banks are always bailed out by the government and continue operating in the subsequent period.

3.5 Government & Central Bank

The government collects taxes on firm and bank profits, as well as on emissions generated by the energy sector. Profits are taxed at a constant rate. The tax charged to the energy sector per unit of emissions is assumed to change at the same (endogenous) rate as nominal GDP. The government's main expenditure consists of unemployment benefits, which are paid as a constant fraction of the current nominal wage for each unit of currently unemployed labour. If one or more banks have failed in a period, the government pays for the bailout of these banks. In addition, the government must pay interest on any debt it has accumulated in the past. Finally, the government must roll over its existing debt in each period. If current tax revenue is insufficient to meet all expenditures and debt repayments, the government issues single-period government bonds to cover the difference. Government bonds are first offered for sale to banks, with any unsold bonds being purchased by the central bank. The current interest rate on government bonds is assumed to be equal to the central bank's lending rate and applies to all outstanding government debt.

The central bank sets an interest rate at which it lends to the banking system following a Taylor rule:

$$r^l_{CB,t} = \iota_1 r^l_{CB,t-1} + (1-\iota_1)(r + \iota_2(\pi^a_t - \pi^*) + \iota_3(U^* - U_t)), \tag{4}$$

where ι_1 is a smoothing parameter, r is a fixed intercept, π^a_t is the current year-on-year inflation rate with π^* being the year-on-year inflation target, U_t being the current unemployment rate and U^* the central bank's target unemployment rate. Since the model runs at quarterly frequency, this annual lending rate is subsequently converted to a quarterly one. If the central bank makes a profit, this is transferred to the government. Conversely, the government covers any losses made by the central bank. Each commercial bank holds a (not remunerated) reserve account at the central bank. Also the fossil fuel sector holds a reserve account at the central bank. This sector is intentionally modelled as 'quasi-external' to the rest of the model to allow for the depiction of an increase in the price of an externally supplied fossil fuel. The sector is therefore not directly linked to the 'domestic' banking system but instead makes and receives payments through central bank reserves.

3.6 Energy

The energy sector consists of a single representative firm employing different plants to produce energy that is used by C-Firms and K-Firms. Energy is produced using both 'brown' and 'green' installations. As is the case for K-Firms, the energy sector engages in R&D in order to develop improved energy production technologies (both 'brown' and 'green').

The existing productive capacity of the energy sector in terms of units of energy producible is denoted as $\mathfrak{K}_{e,t-1}$, which can be subdivided into a capacity for producing 'brown' ($\mathfrak{K}^{de}_{t-1}$) and 'green' ($\mathfrak{K}^{ge}_{t-1}$) energy. Green and brown energy plants differ as follows:

- Brown energy production has a positive emission intensity, while green energy production does not give rise to emissions. R&D can lead to new brown energy technology vintages with a lower emission intensity.
- The production of brown energy requires the purchase of a fossil fuel input from the fossil fuel sector, while green energy plants can produce energy at zero cost. R&D can lead to the development of brown energy technology vintages with a lower fossil fuel input requirement per unit of energy produced.
- The expansion of productive capacity carries a positive cost for green energy plants, but is assumed to be costless for brown energy plants. R&D can lead to green energy technology vintages with a lower investment cost per unit of capacity.

If total energy demand from firms in t exceeds the available productive capacity, the energy sector engages in expansion investment. It is assumed that capacity expansion takes place instantaneously such that the production of final output is never constrained by energy availability. For simplicity, and since we are chiefly interested in the short- to medium-run macroeconomic implications of energy price shocks, we assume that the shares of investment in brown and green technologies are fixed.[4] The model is calibrated such that any capacity expansion cost can be paid out of retained earnings, meaning that the energy sector never requires credit. All energy production plants are assumed to have a uniform and fixed lifetime, after which they are scrapped.

Once capacity has been expanded if necessary, the energy sector produces the energy demanded by firms. It does so by activating plants in ascending order of production cost. Since green energy can be produced at zero marginal cost, green energy plants are activated first, followed by the most efficient brown plants.

The uniform price of energy to be paid by all firms is given by an additive mark-up $\mu_{e,t}$ on the unit cost of energy production of the least efficient energy plant activated in t (i.e. the infra-marginal

[4] Under the calibration of the model used here, a temporary energy price shock as that examined below would in any case have a very limited impact on the energy mix.

cost, which is zero if only green energy is produced), $mc_{de,t}$:

$$p_{e,t} = \mu_{e,t} + mc_{de,t}. \tag{5}$$

Note that the price of energy is higher when brown plants are employed to produce energy due to their higher electricity-generation cost. In order to keep the magnitude of the energy price in line with the rest of the economy, $\mu_{e,t}$ is assumed to grow at a rate given by a weighted average of past changes in the nominal wage.

As is the case for K-Firms, the energy sector devotes a fixed share of its revenue to R&D activities, which take the form of hiring labour. This is further split into R&D expenditure on brown and green technologies, with the shares being given by the shares of brown and green energy in total energy produced in t. Innovation follows the same logic as in the case of K-Firms, being determined through a two-step stochastic process detailed in Appendix C.

3.7 Fossil fuels

In order to enable the simulation of an increase in the price charged by an external supplier of fossil fuels, we introduce a stylised fossil fuel sector which supplies any quantity of fossil fuel demanded by the energy sector at a predetermined price $p_{f,t-1}$ abstracting from extraction costs. In the absence of exogenous shocks, p_f is assumed to grow following a weighted average of past changes in the nominal wage $\overline{\Delta_{w,t}}$ (as is the case for $\mu_{e,t}$ in equation (5) shown above) to assure the fossil fuel price does not exhibit a secular trend.

$$p_{f,t} = p_{f,t-1} * \overline{\Delta}_{w,t} \tag{6}$$

The energy sector's demand for fossil fuel, ff_t^d, is determined by the model's current demand for energy and the fossil fuel input necessary to produce this energy given the characteristics of currently existing plants in the energy sector. The revenue of the fossil fuel sector is hence given by

$$FF_t = p_{f,t} ff_t^d \tag{7}$$

As mentioned previously, the fossil fuel sector holds a reserve account with the central bank, meaning that a sale of fossil fuels results in a reduction of deposits and reserves on the balance sheets of the banking sector, mimicking the effects of an import of fossil fuel. All revenues from the sale of fossil fuels accumulate in this reserve account. In each period, the sector pays a very small fraction d_f of its accumulated wealth to the household sector. This assumption is made to ensure that the wealth of the fossil fuel sector relative to that of other sectors or e.g. as a ratio of domestic GDP does not grow continuously.

$$Div_{f,t} = \delta^F \big(R_{f,t-1} + FF_t\big) \tag{8}$$

By setting the parameter δ^F to a small value, this setup can be used as a stylised depiction of an external fossil fuel producer which receives revenue from the 'domestic' economy but makes only very small payments to the rest of the system.

4 Calibration and validation

Prior to simulating energy price shock scenarios, we calibrate both the business cycle and growth dynamics of our model to obtain a baseline run intended to depict the EU27 region with 2010Q1 representing the first post-transient simulation period. Regarding long-term growth rates of GDP, endogenous carbon emissions, and energy use, the target statistics on which we calibrate our model are drawn from the Shared Socioeconomic Pathways (SSPs), specifically SSP2 (Koch and Leimbach, 2023), and scenarios produced by integrated assessment models (IAMs), taken from the scenario database of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Byers et al., 2022). Business cycle moments, meanwhile, are calibrated on historical macroeconomic data for the EU27 using the method of simulated moments (MSM, see e.g. Reissl 2020; Schmitt 2020. Details on the data and methods used are provided in Appendix A.

Our calibration process consists of two steps. First, starting from the rough baseline calibration shown in Reissl et al. (2024), we manually modify the subset of parameters chiefly responsible for governing long-term growth dynamics in order to reproduce the target growth rates as closely as possible. Having determined a region of the parameter space in which the model is able to match these rates closely, we apply the formal MSM procedure detailed in Appendix A to calibrate a subset of parameters which are chiefly responsible for determining the business cycle characteristics (e.g. standard deviations and autocorrelations of the main macroeconomic variables) of the model. Following calibration, we carry out an extensive quantitative and qualitative validation procedure,[5] demonstrating that the model successfully matches the business cycle statistics drawn from the empirical data, as well as the long-term growth dynamics provided by the SSP and IAM scenario data. In addition, Appendix A also contains the table giving the rich list of macroeconomic and microeconomic stylised facts reproduced by the DSK model (cf. Dosi et al., 2010, 2017a).

Following the validation exercise, we use the calibrated model to simulate a baseline scenario without a shock to the price of fossil fuels. This benchmark scenario will allow us to isolate and visualise the impacts of the energy shock scenarios presented in the next section in terms of deviations from the baseline. One simulation period in the model corresponds to one quarter. The baseline and all shock scenarios shown below are simulated for 400 post-transient periods, each for

[5] On the empirical validation of agent-based models see Fagiolo and Roventini (2017); Fagiolo et al. (2019); Lamperti et al. (2018b).

the same set of 108 seeds of the pseudo-random number generator. Since we are here only concerned with the short-run impacts of fossil fuel price shocks, the plots below show impacts up to the period corresponding to 2030Q1.[6]

5 Scenarios

All shock scenarios are characterised by an identical, sudden increase in the price of domestically produced energy driven by an exogenous shock to the price of the imported fossil-fuel input needed for the production of 'brown' energy. The shock begins during the simulation period corresponding to the final quarter of 2021, and is calibrated to produce an almost twofold increase in the energy price by the second quarter of 2022. The energy price peaks in that quarter and remains elevated throughout 2022, before the shock begins to fade away in early 2023, with the price of energy ultimately reverting to the baseline trajectory, as illustrated in Figure 1. The magnitude of the energy price increase we consider is hence comparable to what has resulted for measures such as the IMF's global price of energy index International Monetary Fund (2024), and we assume a relatively high persistence in line with existing literature (Ghoshray, 2018; Kruse and Wegener, 2020; Turco et al., 2023, cf.).

The institutional setting characterising the different shock scenarios we examine is defined by the reactions of firms, households and the government.[7] Depending on the simulation setting, consumption good firms aim to protect their profit margins by passing on a larger or smaller fraction of the increase in the energy cost into their final selling prices with the rest being absorbed by a decrease in their mark-ups. C-Firms may also pass a larger or smaller fraction of the post-shock *decline* in the cost of energy into their prices, with the remainder being absorbed by an increase in their mark-ups. These upward and downward pass-through rates are exogenous parameters whose value changes across scenarios and which mimick different power relationships between firms and workers. Firms' effective markup therefore consists of two components: one, as described in Section 3, which depends on market shares, and another influenced directly by their pass-through behaviour, independent of market shares. The decision to pass on energy price variations results in an effective markup that can be higher or lower than if it were determined solely by market shares.

Households react to the inflationary pressures caused by the energy price increase by adjusting their nominal wage demands. Depending on the sensitivity of nominal wages to the inflation rate (parameter ψ_1 in Equation 2), they are able to protect the real wage rate to differing extents. The higher the value of ψ_1, the greater the extent to which purchasing power is maintained, but the

[6] The calibration and simulation runs shown in this paper were produced on the 'Zeus' High Performance Cluster of the Euro-Mediterranean Center on Climate Change (CMCC), running Linux CentOS 7.6 x86_64 on compute nodes with Intel Xeon Gold 6154 CPUs. The executable was compiled on E.K.'s computer using GNU GCC 11.4.0 and S.R.'s computer using GNU GCC 9.4.0. and consistency checks were carried out.

[7] The central bank's reaction is not the focus of our experiments. Throughout all scenarios, it remains unchanged, with the central bank following the Taylor rule given in Equation 4 with an inflation target of 2%.

greater are the potential inflationary pressures stemming from the surge in unit labour costs. The parameter ψ_1 thus captures different institutional regimes in the labour market. It is exogenous and varies in the scenarios shown below.

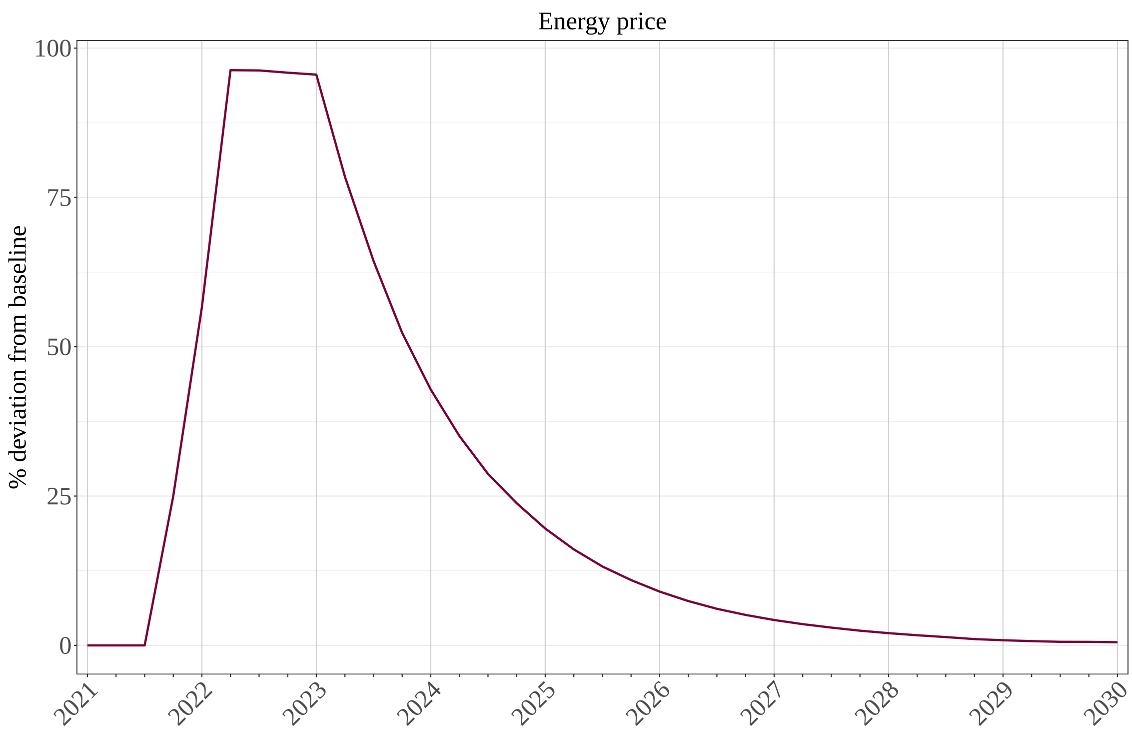

Figure 1: Percentage deviation of the simulated energy price from its baseline trajectory the shock to the price of fossil fuels. The line represents average across 108 model simulations with different, reproducible seeds. Bands (too narrow to be visible) are 95% confidence intervals.

Finally, the government can implement redistributive policies through temporary transfer payments to households and/or firms. The aggregate sum of these payments is determined according to the funds required to offset the surge in energy prices for firms. The latter are computed as the difference between the energy price following the shock and the baseline price. As the energy shock unfolds, the total amount of transfer payments increases until it reaches a maximum at the peak of the energy crisis, then decreases to zero when the shock is over. The government decides how to allocate the transfer payments, dividing the total transfer payment between households and firms. For instance, a 75%-25% division is used below to indicate that the government allocates 75% of the transfer sum to households, with the remaining 25% being allocated to firms.

By varying the values of the pass-through rates, the sensitivity of the nominal wage rate to inflation, and the allocation of transfer payments, we construct three main scenario settings:

- The first scenario (hereafter referred to as *EU 2022 policy mix*) corresponds to a situation as close as possible to the empirical developments occurred in the European Union since 2021. We calibrate all parameters related to the institutional settings on empirical data. For upward and downward pass-through rates, we rely on the existing literature which has been able to estimate them for France (Lafrogne-Joussier et al., 2023) and Denmark (Dedola et al., 2021). We use an upward rate of 100% and a downward rate of 60%. This means that firms pass on 100% of the energy price increase into their final selling prices, but only 60% of the subsequent decrease, meaning that they increase their mark-up as the energy price reverts back toward its baseline trajectory. The sensitivity of nominal wages to inflation deviations from the target rate is included in the vector of parameters estimated during the empirical calibration of the model on EU data, and we use that estimated value (0.113) in this scenario. For the shares of financial transfers allocated to households and firms, we use the Bruegel database on national fiscal policy responses to the energy crisis (Sgaravatti et al., 2023). We use it to deduce the shares of financial transfers and tax breaks which have been allocated to households and companies in the European Union, arriving at 80% and 20% respectively.
- The second scenario (hereafter referred to as *No policy*) is identical to the first with the exception of government transfer payments, which are set to 0.
- The final category of scenarios (hereafter referred to as *Alternative policy*) encompasses other strategies that the government might have pursued in response to the energy price crisis, such as distributing transfer payments between households and firms according to shares different from the *EU 2022 policy mix* scenario, or imposing some form of price controls on final output prices, effectively intervening on the upward and/or downward pass-through rates.

6 Results

In this section, we assess the effectiveness of the EU 2022 policy mix described above. Specifically, we address two interrelated questions. To what extent does the foregoing policy mix succeed in minimizing the impact of an energy price shock akin to the one caused by the war in Ukraine (see section 6.1)? Are there alternative policy measures that could have been more effective (see section 6.2)?

6.1 The EU 2022 policy mix

To determine whether the empirically calibrated policy intervention is effective in mitigating the macroeconomic impact of the energy price shock, we compare the *EU 2022 policy mix* scenario to the *No policy* one using four metrics: i) firms' balance sheets indicators (ratio of bad debt to GDP, bankruptcies), ii) real macroeconomic variables (employment rate, GDP), iii) functional income distribution, and iv) inflation. We also assess whether the EU 2022 policy mix entails the possibility of triggering a wage-price spiral. In Appendix B, we provide additional validation of the model, showing that, beyond being calibrated for non-crisis periods, it realistically reproduces the economic trajectory of the EU27 during the energy crisis.

After the fossil-fuel price shock, the price of energy rises rapidly, leading to an increase in the cost of inputs for the production of final output. With an upward pass-through rate of 100%, firms fully pass on this increase to their final selling prices. However, this protection of profit margins comes at the expense of real wages. This negatively impact on household consumption and lead firms to reduce capital investment. The full pass-through of increased energy costs turns out to be self-defeating for some firms, which by protecting their profit *margins* hamper their profit *volumes*, leading to a spike in bad debt and bankruptcy rates (see Figure 2, top). In appendix B, we consider different cases with partial pass-through of the energy shock. We find that loan defaults and firm bankruptcies peak at levels close to those observed in the full pass-through scenario. In presence of partial pass-through, the profitability of the firms is reduced and their financial fragility increases. Simulation results thus show that firms cannot avoid a surge in bankruptcies after a positive energy price shock due to a mix of lower demand and reduced profitability.

At the macroeconomic level, in the *No policy* scenario, the energy price shock leads to a recession characterised by a decrease in both the employment rate and real GDP (see Figure 2, bottom). Transfer payments to households and firms help mitigate these negative impacts by preventing the collapse of aggregate consumption, cushioning firm profits and holding the employment rate steady. Overall, the empirically calibrated policy mix is very successful at smoothing out the effects of the energy price shock on real GDP and also reduces loan defaults and firm bankruptcies compared to the case of no policy intervention (see Figure 2).

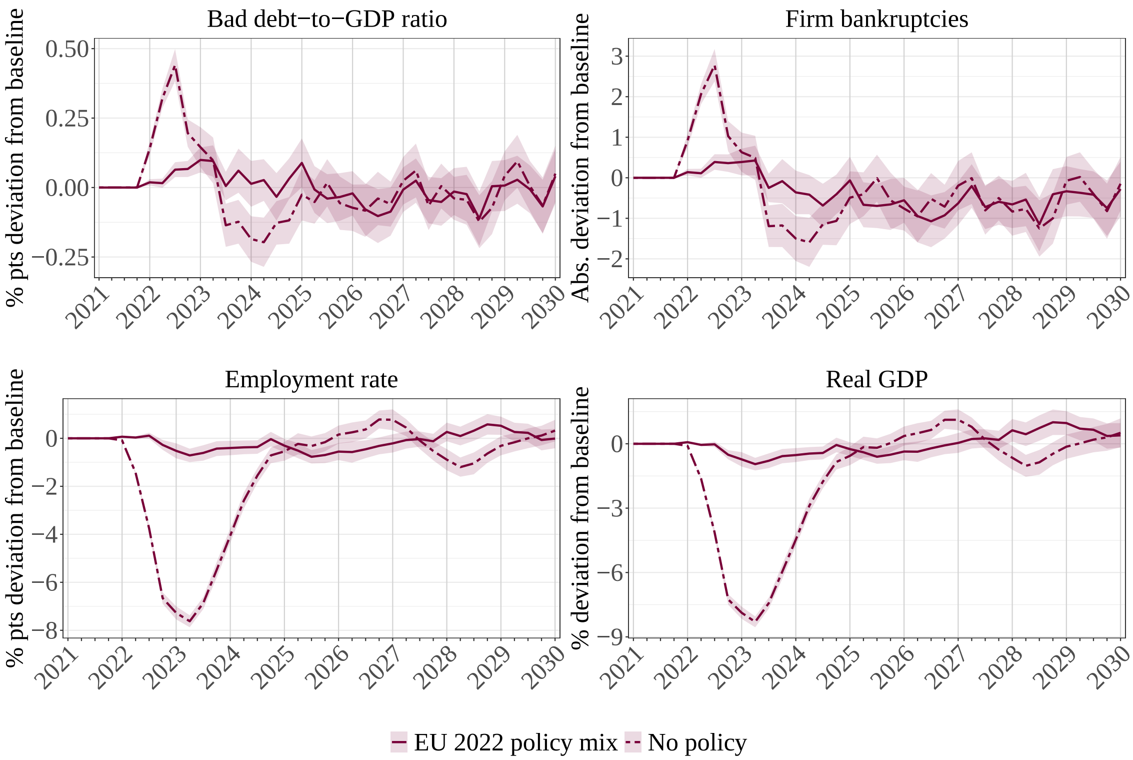

Figure 2: Ratio of bad firm bad debt to nominal GDP (top left), number of firm failures (top right), employment rate (bottom left), and real GDP (bottom right), with (solid) and without (dashed) government intervention. Time series are shown as absolute or percentage point deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

Let us now consider the distributional impact of the energy price shock. In the *No policy* scenario, the decline in aggregate demand leads to a reduction in both the share of wages and the share of consumption and capital firm profits (excluding profits from banks, the energy sector, and the fossil fuel sector) compared to the no-shock scenario (see Figure 3). However, as the energy price peaks and begins to recede, production costs decrease, firms are then able to stabilise their profits and their share in total income begins to increase. This is not the case for the real wage and the wage share which continues to decline due to the high unemployment rates. Since firms only partially pass on the decrease in the energy price to their final selling prices, the wage share recovers much more slowly and remains permanently below its baseline value as the real wage rate. By effectively increasing their mark-up rate while the energy price decreases, firms capture a larger share of total income in the economy, at the expense of wages. This results in a persistent change in the functional distribution of income. In the next subsection dedicated to alternative policy interventions, we provide a closer examination of the role of downward pass-through rates, showing that the functional distribution only returns to its pre-crisis configuration when downward pass-through is complete, and that low downward pass-through rates significantly slow down the post-shock recovery of GDP and employment.

In the *EU 2022 policy mix*scenario, transfer payments primarily targeting households allow to reduce the decline of the real wage rate from -12% to around -5% (see right panel of Figure 3). Together with the transfer payments to firms, this also indirectly prevents the initial decrease in the share of firm profits (see left panel of Figure 3) by dampening the fall of household consumption. However, transfer payments are not able to reverse the permanent shift in functional income distribution in favour of firm profit income (see left panel of Figure 3).

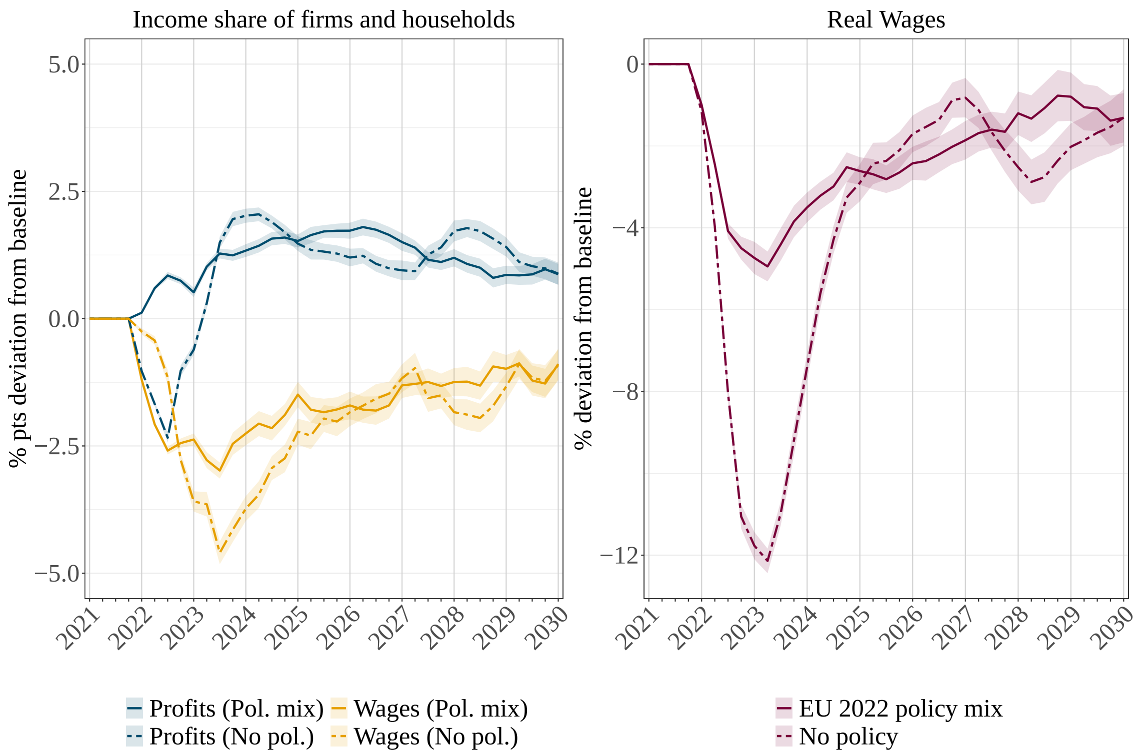

Figure 3: Wage and firm income shares including transfer payments and real wage rate with (solid) and without (dashed) government intervention. Time series are shown as absolute deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

In order to study the inflationary consequences of the energy price shock, we undertake a decomposition of the simulated Consumer Price Index following the approach employed by institutions such as the OECD (OECD, 2023), the IMF (International Monetary Fund, 2023) and the ECB

(Hahn, 2023). More specifically, by constructing an index for each component of firms' production costs and by calculating their weight in total production costs, we can decompose the dynamics of the CPI inflation in three distinct components related to labour costs, profit margins and energy costs.[8] Figure 4 illustrates our decomposition of year-on-year Consumer Price inflation. Prior to the shock, inflation is stable around the 2% target, chiefly driven by nominal wage growth. When the shock occurs at the end of 2021, inflation increases abruptly, primarily driven by rising energy costs, but also by an increase in absolute firm markups due to the 100% upward pass-through which keeps the markup *rate* constant. Comparing the *EU 2022 policy mix* scenario to the *No Policy* scenario reveals that government intervention slightly exacerbates and prolongs the initial inflationary phase. This is chiefly due to additional pressure from labour cost, which continues to increase as the spell of high unemployment taking place in the *No Policy* scenario is avoided (see Figure 2). However, the empirically calibrated policy intervention also prevents the occurrence of a later inflationary episode which is present in the *No Policy* case. In such a scenario, the recession induced by the energy price shock is followed by a strong recovery during which labour cost increases. This recession-recovery dynamic is avoided in the *EU 2022 policy mix* scenario thanks to targeted payment transfers to households, which compensate for the drop in aggregate demand caused by firms passing the increase in energy prices onto their selling prices. Generally, Figure 4 reveals that for the baseline level of sensitivity of the nominal wage to inflation, the empirically calibrated mix of transfer payments does not result in excessive additional inflation, and a wage-price spiral never occurs.

[8]In the decomposition analyses presented by the OECD, IMF, and ECB, profits and energy costs are not reported separately.

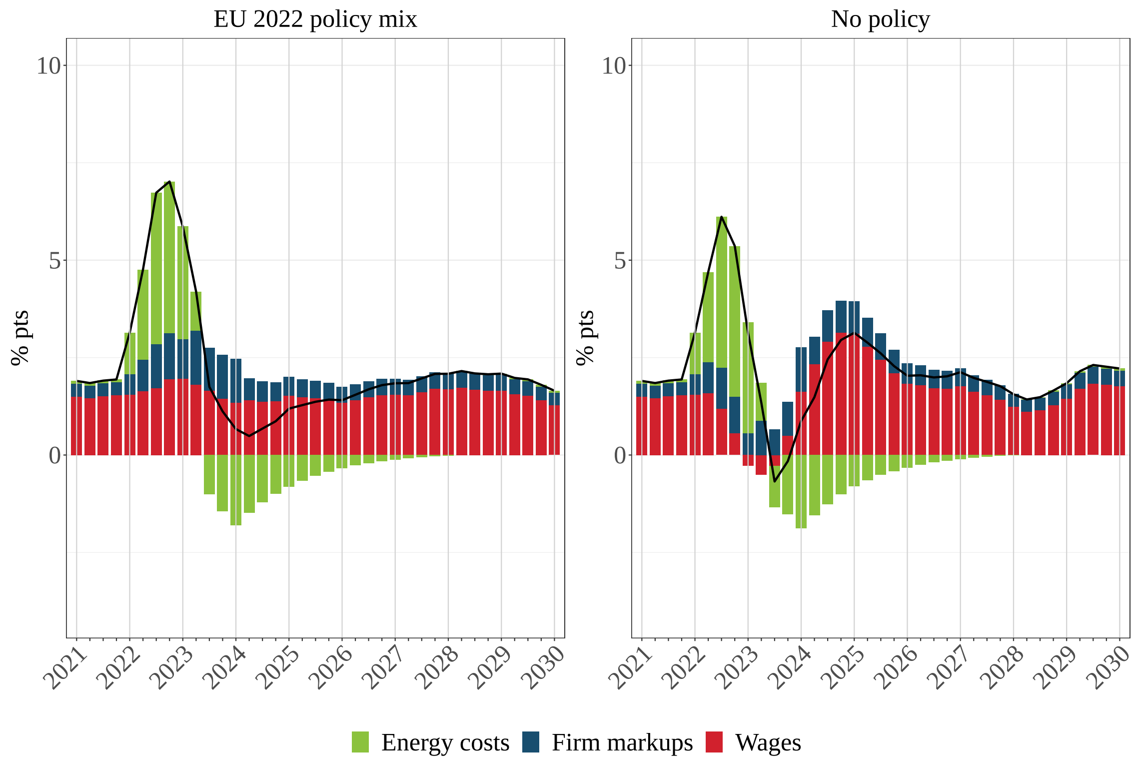

Figure 4: Year-on-year CPI inflation decomposition with (left) and without (right) government intervention. Numbers are averages across 108 model simulations with different, reproducible seeds. Black line represents CPI inflation rate.

To test the robustness of this result, we simulate a series of scenarios featuring the EU 2022 policy mix and increasing levels of the sensitivity of the nominal wage rate to inflation (parameter ψ_1). Rather than imposing an exogenous shock in a predetermined period to this parameter, we assume that periods of high inflation can lead to a 'regime shift' producing an increase in the sensitivity of nominal wage claims to inflation in line with the literature on conflict inflation (Arestis and Sawyer 2005; Setterfield 2007; Lavoie 2024; Lorenzoni and Werning 2023;Wildauer et al. 2023). In particular, we assume that if year-on-year inflation is sufficiently high (at least 5%) for a sufficiently long period (3 quarters), the baseline value of ψ_1 (0.113) is multiplied by a fixed factor and subsequently remains at this higher value as long as these thresholds are exceeded. We test several values for this factor (4, 6, 8, 10, and 12) to identify any threshold effects. The results are presented in Figure 5. We observe that the higher the sensitivity of nominal wage claims to inflation, the higher the wage factor increases in the decomposition, and the higher the rate at which inflation peaks in the immediate aftermath of the energy price shocks. Additionally, higher values of ψ_1 also increase the persistence of elevated inflation rates. However, labour costs keep being anchored to the inflation target, except for very high and arguably unrealistic values of ψ_1. Indeed, Figure 5 suggests that there is a threshold effect, with instability resulting once the multiplicative factor reaches 10, implying a value of ψ_1 larger than 1 with nominal wages growing at a faster pace than prices. Notably, this threshold was not surpassed during the energy price shock, particularly during the period of substantial government financial support to the economy. This is evident from the clear fall-off in compensation per employee relative to CPI inflation in the EU between 2022 and 2023 (Checherita-Westphal and Vlad, 2023). Consequently, we conclude there were no significant risks of a wage-price spiral getting out of control, despite tax breaks focusing on households. This aligns with the findings of Alvarez et al. (2022), who observed that only a small fraction of wage-price spiral episodes have persisted or intensified since 1960, with both inflation and wages tending to stabilize over time.

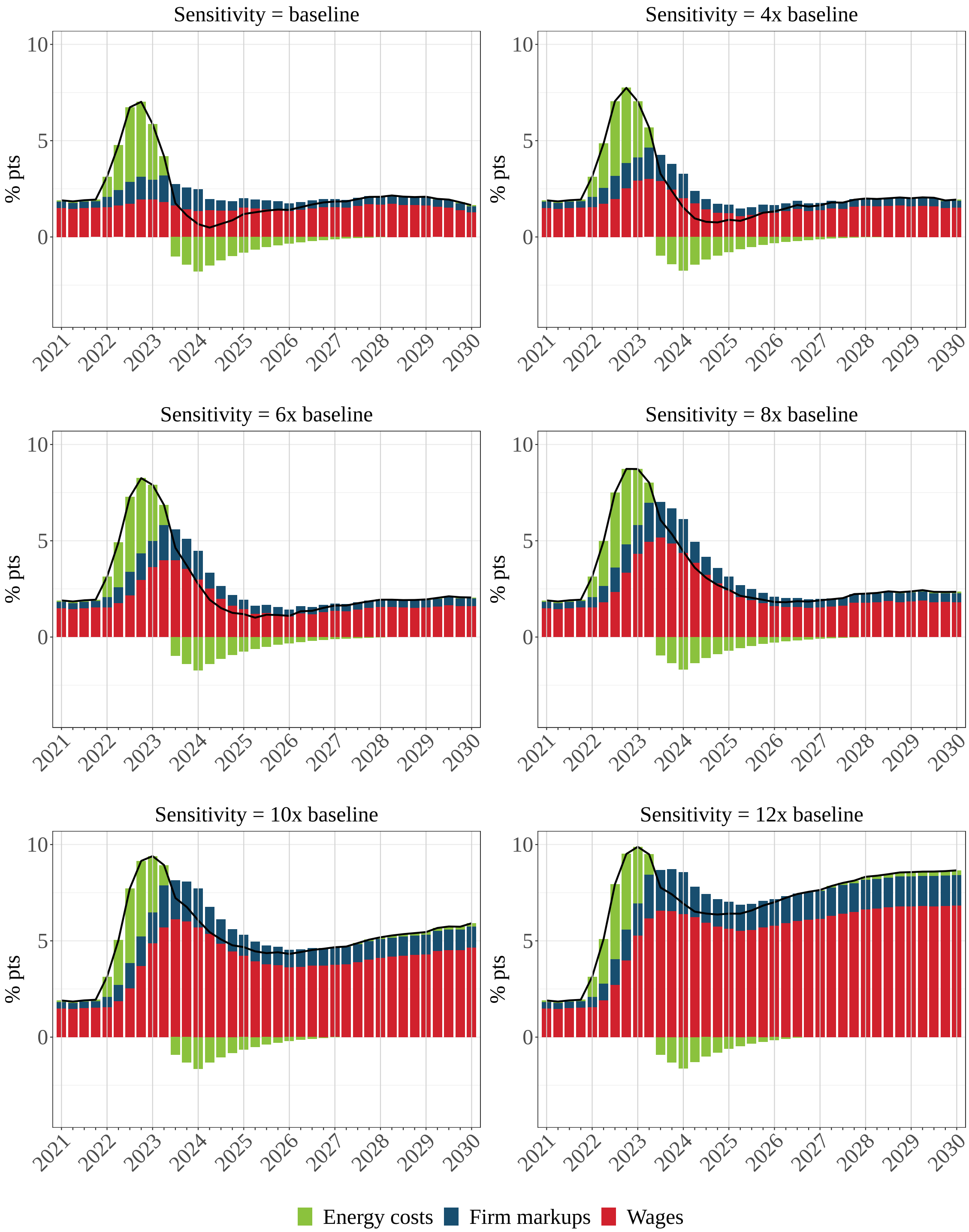

Figure 5: Year-on-year CPI inflation decomposition for empirically calibrated transfer payments and increasing sensitivity of nominal wages to inflation. Numbers are averages across 108 model simulations with different, reproducible seeds. Black line represents CPI inflation rate.

6.2 Alternative policy interventions

We now compare the empirically calibrated *EU 2022 policy mix* scenario (with 80% of transfer payments distributed to households and 20% to firms) to the *Alternative policy* scenarios. We first look at different distributions of transfer payments between households and firms. We then investigate price control policies intervening on the upward and/or downward pass-through rates. We compare these policy scenarios along the same dimensions as in the previous subsection.

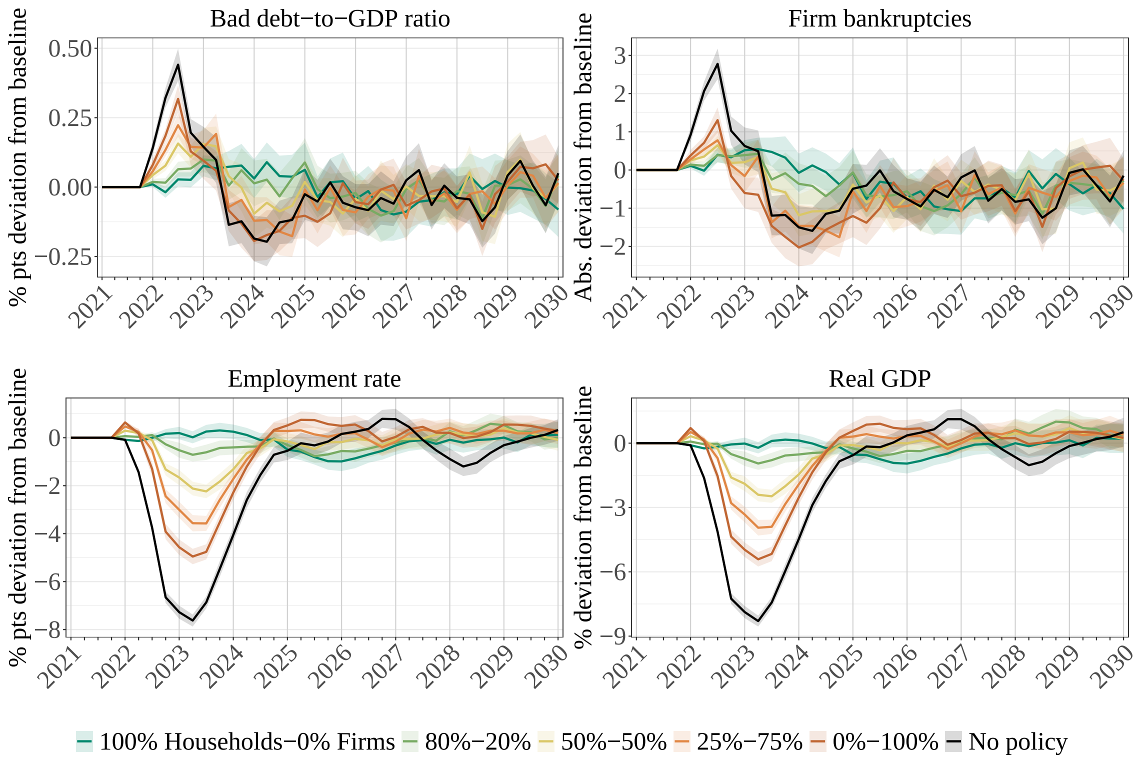

Figure 6: Ratio of bad firm bad debt to nominal GDP (top left), number of firm failures (top right), employment rate (bottom left), and real GDP (bottom right), for different distributions of transfer payments between households and firms. Time series are shown as absolute or percent deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

Figure 6 suggests that the effectiveness of transfer payments at mitigating the impacts of the energy price shock varies strongly depending on how they are targeted. When they are primarily focused on firms, defaults and bankruptcies are reduced relative to the *No Policy* case. At the same time, transfer payments to firms are less effective at sustaining employment and GDP than transfer payments to households, meaning that firm profit volumes still decline and defaults increase relative to the baseline. The EU 2022 policy mix in which transfer payments are concentrated on households hence proves very effective compared to other interventions.

Figure 7: Wage and firm income shares for different distributions of transfer payments between households and firms. Time series are shown as absolute deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

The strong impact of varying the distribution of transfer payments is shown by Figure 7, which shows the consequences for functional income distribution. When financial support is strongly concentrated on firms, the initial decline in the wage share is exacerbated while transfers focused on households smooth out the dynamics of functional distribution. In this sense, the EU 2022 policy mix does a comparatively good job of alleviating distributional conflicts arising from the energy crisis. However, regardless of the configuration of transfer payments, the partial pass-through of energy price decreases leads to a permanent shift in functional distribution toward profits due to an increase of the effective mark-up rate.

Figure 8 provides an overview of the effects of different policy configurations on inflation dynamics. Regardless of how transfer payments are targeted, they slightly exacerbate the initial inflationary shock. Payments primarily targeting firms result in a shorter duration of the initial inflationary episode compared to those mainly focusing households since the former are less effective at supporting employment. At the same time, the phase of elevated inflation during the post-crisis recovery which is present in the *No Policy* scenario also occurs when transfers are focused on firms.

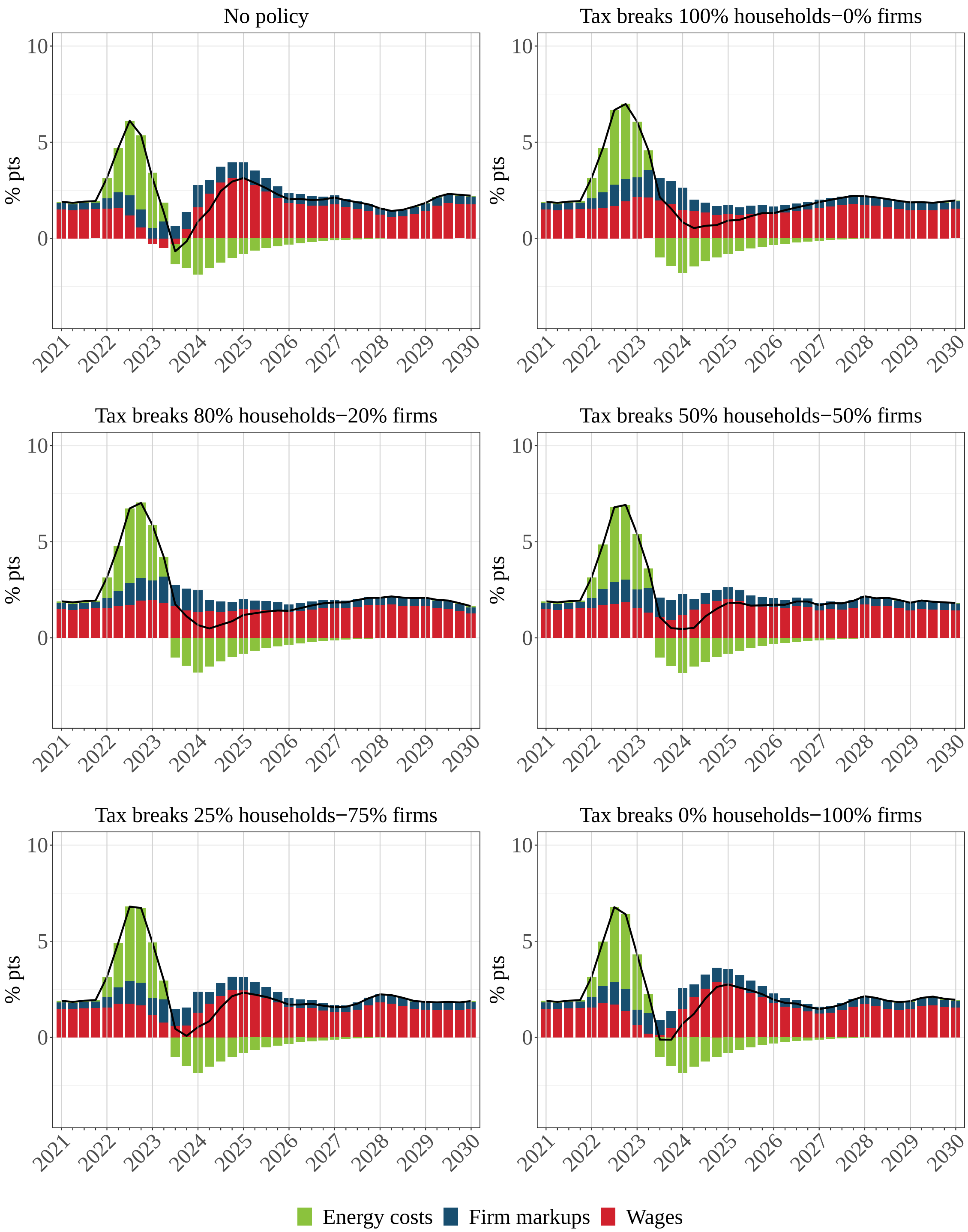

Figure 8: Year-on-year CPI inflation decomposition for various configurations of transfer payments. Numbers are averages across 108 model simulations with different, reproducible seeds. Black line represents CPI inflation rate.

Since we show that transfers alone, although effective in mitigating the macroeconomic consequences of the energy shock, do not address the distortion of the functional distribution of income caused by firms' incomplete pass-through of decreased energy prices, we then compare several scenarios with different downward pass-through rates. Note that the higher this rate, the more firms pass on the post-shock decrease in energy costs to their final selling prices. By keeping the upward rate at its empirically calibrated level of 100%, this experiment mimics a form of price control policy (or strong widespread antitrust interventions) that force firms to cut prices as the energy shock subsides.[9]

Figure 9 shows that while firm defaults and bankruptcies are virtually unaffected by varying the downward pass-through rate, the latter is an important determinant of the post-shock dynamics of real GDP and the employment rate. Specifically, the lower the degree to which firms pass on the energy cost decrease (and instead increase their mark-up rates), the slower the economic recovery becomes.

[9]In Appendix B, we compare scenarios with different pass-through rates, assuming that upward and downward pass-through rates are identical. This additional experiment simulates price control policies that not only force firms to reduce prices as the energy shock diminishes, but also cap firm selling prices during the shock.

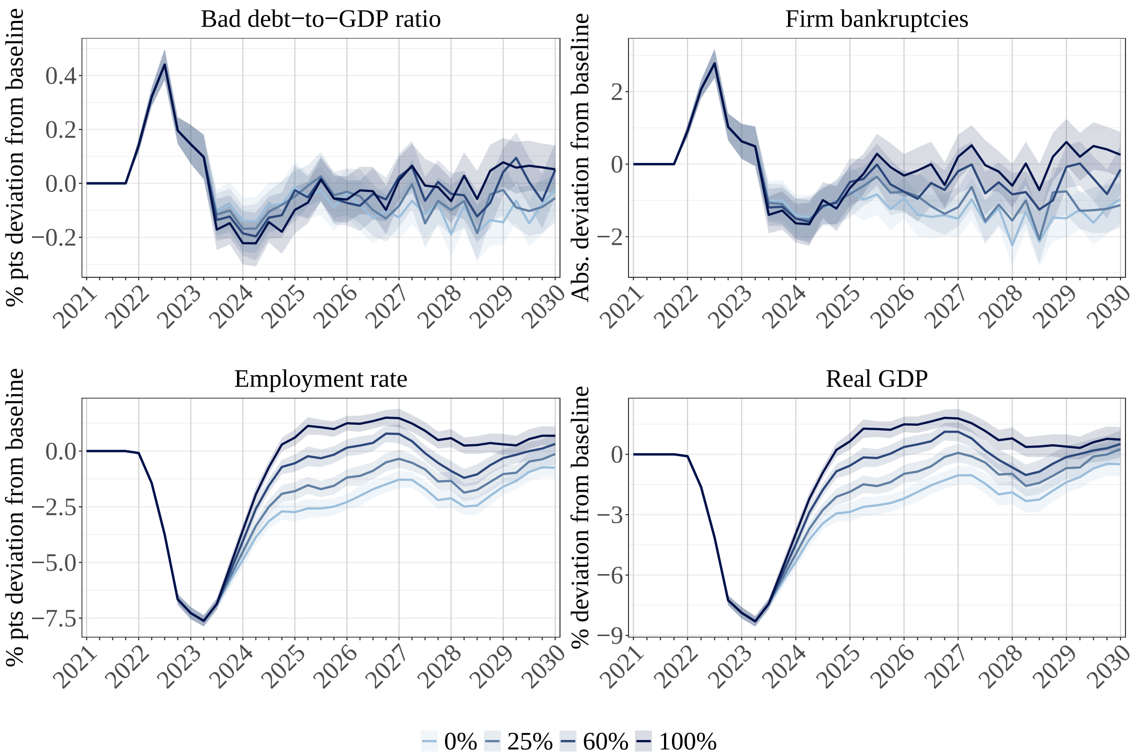

Figure 9: Ratio of bad firm bad debt to nominal GDP (top left), number of firm failures (top right), employment rate (bottom left), and real GDP (bottom right), for various downward pass-through rates. Time-series are shown as absolute or percent deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

This latter effect is chiefly explained by the distributional consequences of the different downward pass-through rates, shown in Figure 10. By only passing on a part of the energy cost decrease, firms' mark-up rate and hence the share of firm profits in aggregate income increase permanently at the expense of the wage share. Since wage income represents the largest share of household income, a decrease in the wage share depresses aggregate demand and hence slows down the post-shock recovery. Conversely, ensuring a complete pass-through of energy cost decreases is crucial for both economic recovery and avoiding distortions in the functional income distribution. Complete pass-through helps restore real GDP and employment rates more rapidly, as the wage share remains stable, maintaining household consumption levels and aggregate demand.

Figure 10: Wage and firm income shares for various downward pass-through rates. Time-series are shown as absolute deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

Since the level of the upward pass-through rate does not vary across the scenarios examined here, the initial spike in inflation caused by the energy price shock is identical in all panels of Figure 11. However, low downward pass-through rates somewhat exacerbate inflationary pressures during the post shock recovery phase. While they slow down the recovery of employment and hence reduces wage growth, the increase in firms' mark-up rates more than compensates for this and fuels "seller's inflation" (Weber and Wasner, 2023).

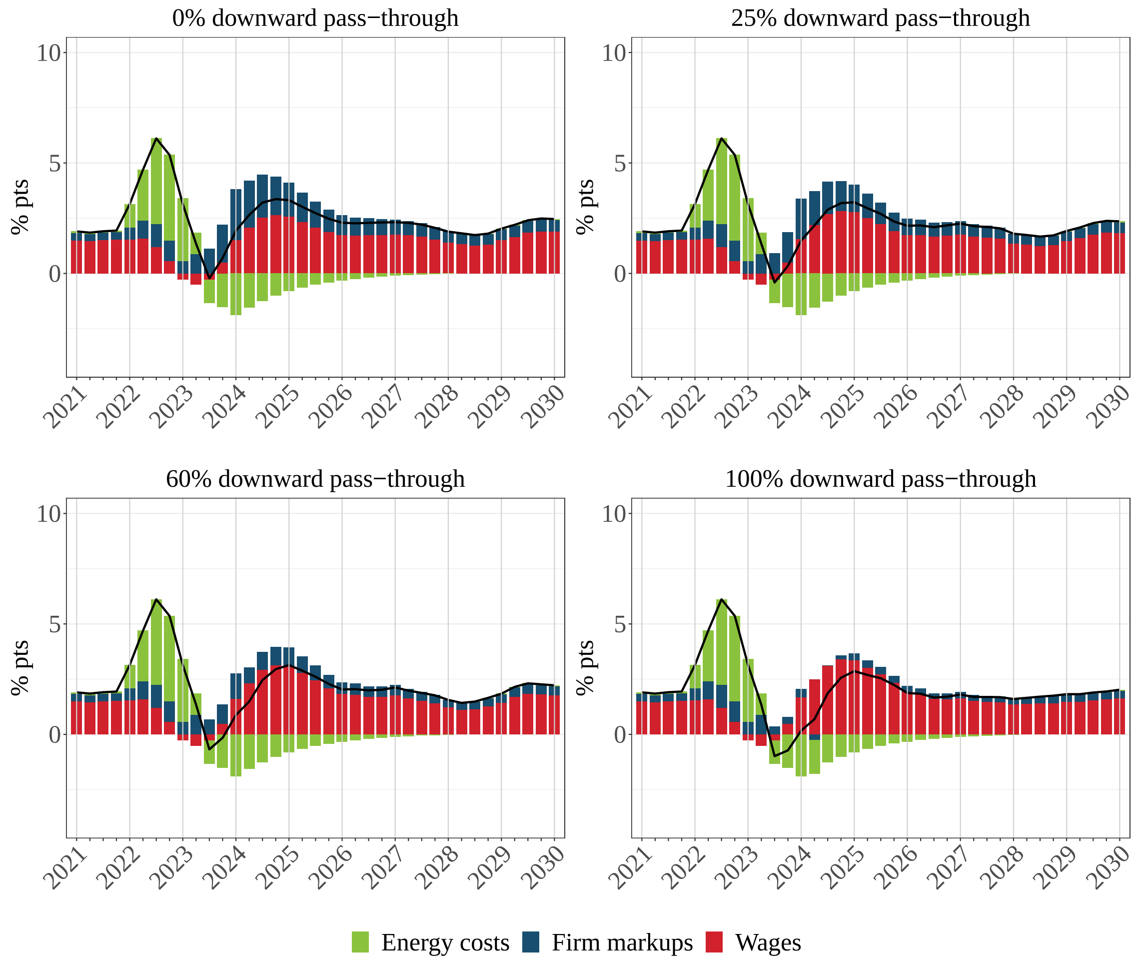

Figure 11: Year-on-year CPI inflation decomposition for various downward pass-through rates. Numbers are averages across 108 model simulations with different, reproducible seeds. Black line represents CPI inflation rate.

These findings, consistent with those of Weber et al. (2024) and Krebs and Weber (2024), highlight the critical role price control policies can play during energy crises. By mandating a complete downward pass-through and preventing firms from using falling energy prices to increase their margins, these policies help ensure that economic growth returns to its pre-crisis trajectory. They also maintain the functional distribution of income and minimize the risks of residual "seller's inflation", hence reducing the likelihood of long-term economic stagnation.

7 Conclusions

This paper employs the Dystopian Schumpeter meeting Keynes model (Lamperti et al., 2018a, 2019, 2020, 2021; Reissl et al., 2024) and calibrates it to EU27 data to examine the effects of an energy price shock akin to that the EU has been facing after the start of the war in Ukraine. We then used different counterfactual simulations to isolate the role of firms' pricing behaviours and nominal wage claims, as well as to evaluate the impact of policy measures.

Our results suggest that an unmitigated energy shock would have resulted in substantial macroeconomic losses. However, a policy intervention using an empirically calibrated distribution of transfer payments - focusing primarily on supporting households and allocating less support to firms, as happened in the European Union - is very effective at limiting the economic fallout from the energy price shock, strongly stabilising both real GDP and employment, and limiting loan defaults and firm bankruptcies. At the same time, such a policy strategy does not produce significant additional inflationary pressures, even when assuming a high sensitivity of nominal wage claims to the inflation rate.

The assessment of the EU 2022 policy mix becomes more nuanced when considering the distribution of functional income. Indeed, while the policy intervention limits the initial decline in the wage share, it does not correct the long-term shift in functional income distribution in favour of firm profits. We find that other policy measures forcing firms to fully pass the decreases in energy costs to prices would be needed to eliminate the shock's effects on functional distribution, thus protecting households' purchasing power and limiting the distributional consequences of energy shocks.

Our work can be extended in different ways. First, we will expand the model to incorporate household heterogeneity and direct household demand for energy, providing a more detailed picture of how energy price shocks impact the entire income distribution. Additionally, we will also consider the possibility for firms to electrify their production and study the impact of energy price shocks on their energy transition. We will examine how this transition may be slowed by a sudden increase in input costs and how different types of support policies for firms, whether targeted or broadly applied, could mitigate this issue. Additionally, we will analyze how these policies can be balanced with support for households to minimize the impact of the energy shock while ensuring that the green transition is not delayed.

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Declaration of competing interest: All authors declare that they have no competing interests.

Data availability: The model code, including the input files used for the simulations shown in the present work, will be made publicly available on Zenodo and GitHub upon publication of a peer-reviewed version of the paper.

CRediT authorship contribution statement: All authors contributed to the conceptualization, design of the experiments, development of the methodology of analysis, discussion of the results and writing. E.K. and S.R. performed all the simulations.

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Appendix A Calibration and validation

This appendix provides additional details on the calibration and validation of the model, describing the data used and the method applied for the calibration of short-run dynamics, and showing additional tables and graphs for validation.

A.1 Data

To determine the average growth rate of real GDP to which we aim to calibrate our model, we make use of the SSP economic growth projections presented by Koch and Leimbach (2023). By aggregating the country-level projections for per-capita GDP to the EU27 level and adjusting for the projected changes in population taken from the same dataset, we calculate an average projected annual growth rate of real GDP from 2010 (which is defined to be the first post-transient year of our simulations) to 2100 for SSP2. We also use the projected changes in population to determine an average annual population growth rate at the EU27 level. The model parameter g_L, denoting the exogenous growth rate of the available labour supply, is then set equal to this average projected growth rate.

Table A1: Statistics calculated from SSP projections and IAM scenario data

Statistic	**Value**
Population growth	-0.000047
GDP growth	0.012335
Ind. energy use growth	0.000223
Emission growth (EU)	0.000316
Emission growth (RoW)	0.004538

Regarding calibration targets for the long run growth rates of carbon emissions and energy use, we turn to scenario data generated by IAMs, drawing on the Scenario Explorer and Database for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Byers et al., 2022). In particular, we make use of the 'EN_NPi2100' scenario, simulated by seven established IAMs as part of the ENGAGE model intercomparison (see Riahi et al., 2021). 'EN_NPi2100' is a scenario in which socioeconomic dynamics follow the projections of SSP2, while only currently ratified climate policies are implemented. We obtain the simulated time-series for final energy use in industry, as well as those for overall emissions of Kyoto Gases for the EU and the rest of the world. Calculating median values across IAMs, we calculate the implied average annual growth rates of energy use in industry and emissions from 2010 to 2100. The resulting growth rates of energy use and emissions for the EU represent target values for our calibration procedure, while the growth rate of emissions for the rest of the world is used as an input for the climate module. Table A1 contains the values of the aforementioned statistics.

While we calibrate the long-run dynamics of the model to match projections of future developments, its short-run characteristics are instead calibrated to reproduce business cycle statistics derived from historical macroeconomic data for the EU27. For this purpose, we obtain quarterly time-series data on real GDP, consumption and gross fixed capital formation (investment) as well as the employment and gross inflation rates from 2001Q1 to 2020Q4 for the EU27 from Eurostat. To derive business cycle statistics from these series, we first deseasonalise them and subsequently apply the Hamilton filter (Hamilton, 2018; Schüler, 2018). We then use the cyclical component of the filtered time-series to calculate a set of moments comprising standard deviations, auto- and cross-correlations.

The calibration procedure then proceeds in two steps. First, starting from a rough baseline calibration, we manually modify those model parameters which play the most important role in determining the long-term growth rates of real GDP, energy demand and emissions to match their empirical counterparts as closely as possible. This chiefly involves modifications of those parameters governing R&D expenditures, innovation probabilities, and the characteristics of innovated technologies in the firm and energy sectors. Having determined a region of the parameter space in which the model matches the targeted long-term growth rates reasonably closely, we then proceed to apply a more formal procedure to calibrate a sub-set of parameters which play an important role in shaping the business cycle dynamics produced by the model.

A.2 Method of simulated moments

In order to arrive at a parameter combination under which the model reproduces the business cycle characteristics of the empirical data as closely as possible, we apply the method of simulated moments (MSM, see e.g. Reissl 2020; Schmitt 2020). Intuitively, the goal of this approach is to find the parameter combination which minimises the (weighted) distance between a vector of moments drawn from empirical data and their simulated counterparts. The set of model parameters we choose to include in the procedure is given in table A2, along with the respective ranges which define the parameter space we consider. This set of parameters was chosen since we know them to be important determinants of the business cycle dynamics produced by the model (while, within a reasonable range of variation which was taken into account when defining the parameter space, not having a major impact on long-run growth trajectories).

We sample 4000 parameter combinations from the parameter space defined by table A2 using latin hypercube sampling and rounding sampled values to two decimal places. For each of these parameter combinations, we then simulate the model 108 times for 400 post-transient periods (i.e. 100 years) with different reproducible seeds for the pseudo-random number generator.

Table A2: Parameters and value ranges included in MSM procedure

Symbol	**Description**	**Range**
Γ	Brochures sent by K-firms (share of curr. clients)	$0.1, 0.2$
χ	Effect of competitiveness on market share	$-1.5, -1.35$
ψ_1	Effect of inflation on wage	$0.1, 0.5$
ψ_3	Effect of unemployment on wage	$0.1, 0.5$
α	Adaptive expectations	$0.1, 0.5$
ι_1	Taylor rule interest rate smoothing	$0.65, 0.8$
ι_2	Taylor rule inflation response	$1, 1.35$
ι_3	Taylor rule unemployment response	$0, 0.3$
η	Used for computing weighted averages of past productivity, wage and CPI changes	$0.75, 0.95$

For each parameter combination, we use the simulated time-series data to evaluate the following loss function:

$$\mathcal{L}(\Theta) = \left(\frac{m(\Theta) - m^e}{m^e}\right)' W \left(\frac{m(\Theta) - m^e}{m^e}\right) \tag{A.1}$$

Θ denotes the vector of parameters included in the procedure. m^e is a vector of empirical moments derived from the cyclical components of the filtered time-series data as described above. In particular, it includes:

- The standard deviations of GDP, consumption and gross inflation.[10]
- The first order auto-correlations of GDP, consumption, investment, and the employment and gross inflation rates.
- The contemporaneous cross-correlations between GDP and consumption, investment, the employment rate and gross inflation.

m^e hence consists of 12 empirical moments. For each parameter combination Θ, we calculate the average across seeds of the corresponding simulated moments from filtered simulated time-series to obtain $m(\Theta)$. W is a weighting matrix, given by the inverse of the variance-covariance matrix of the empirical moments which is obtained through bootstrapping (cf. Franke and Westerhoff, 2012) using the *tsboot* function (block resampling with fixed block lengths of 10) of the *boot* package for R Davison and Hinkley (1997); Canty and Ripley (2024).

[10] The standard deviations of the employment rate and investment were purposely excluded from the MSM procedure since, as is common for macroeconomic ABMs, the model was found to be unable to closely reproduce them, with both simulated investment and employment consistently being excessively volatile relative to their empirical counterparts for otherwise reasonable macroeconomic dynamics. They are however included in the validation exercise presented below.

Table A3: Estimated parameter values and standard errors (SE)

Parameter	**Value**	**SE**
Γ	0.194	0.0416
χ	-1.467	0.2298
ψ_1	0.113	0.0104
ψ_3	0.444	0.0443
α	0.278	0.0274
ι_1	0.777	0.1500
ι_2	1.186	0.1722
ι_3	0.100	0.0082
η	0.921	0.0633

Table A3 shows the parameter values resulting in the smallest observed value of the loss function. For each parameter value, the table also reports the corresponding standard error. Standard errors are calculated through the procedure described by Franke (2009), involving the use of partial derivatives of the deviation of simulated from empirical moments with respect to individual parameter values, which are obtained computationally by pertubing each parameter value in turn and recording the change in the deviation between simulated and empirical moments.

A.3 Validation

Following the calibration of model parameters, we carry out a quantitative and qualitative validation procedure. Table A4 provides a quantitative comparison of the empirical and simulated business cycle statistics, with the fourth column indicating whether a particular moment has been included in the MSM calibration procedure. The table shows that the model does a satisfactory job at reproducing many of the examined statistics, though somewhat larger discrepancies exist even beyond the standard deviations of investment and the employment rate which were purposely excluded from the calibration procedure.

Figures A1 and A2 plot the empirical and simulated auto- and cross-correlation functions of the main macroeconomic variables. Consistently with table A4, they show that the model does a better job at reproducing certain auto- and cross-correlations than others, with the overall fit appearing satisfactory.

Table A4: Comparison of empirical and simulated moments. Statistics are calculated from empirical and simulated time-series to which the Hamilton filter has been applied. Simulated numbers represent averages across 108 model simulations with different, reproducible seeds. Numbers in parentheses give 95% confidence intervals

Description	**Empirical**	**Simulated**	**MSM**
Standard deviation of GDP	0.02471 (0.02461, 0.02481)	0.02632 (0.02583, 0.02681)	✓
Standard deviation of Consumption	0.01775 (0.01769, 0.01781)	0.01711 (0.01679, 0.01743)	✓
Standard deviation of Investment	0.04866 (0.04844, 0.04889)	0.20606 (0.20199, 0.21013)	×
Standard deviation of Employment rate	0.00887 (0.00882, 0.00891)	0.01835 (0.01807, 0.01863)	×
Standard deviation of Inflation	0.01018 (0.01015, 0.01021)	0.01015 (0.01001, 0.01030)	✓
1st order autocor. of GDP	0.79325 (0.79175, 0.79475)	0.77903 (0.77178, 0.78628)	✓
1st order autocor. of Consumption	0.82253 (0.82109, 0.82399)	0.82628 (0.82176, 0.83079)	✓
1st order autocor. of Investment	0.77911 (0.77732, 0.78089)	0.55650 (0.54162, 0.57139)	✓
1st order autocor. of Employment rate	0.80006 (0.79861, 0.80150)	0.67046 (0.66270, 0.67822)	✓
1st order autocor. of Inflation	0.77901 (0.77769, 0.78033)	0.65767 (0.65111, 0.66423)	✓
Contemp. crosscor. GDP-Consumption	0.86713 (0.86609, 0.86816)	0.95711 (0.95551, 0.95872)	✓
Contemp. crosscor. GDP-Investment	0.78090 (0.77845, 0.78336)	0.68162 (0.67381, 0.68944)	✓
Contemp. crosscor. GDP-Employment rate	0.45980 (0.45482, 0.46477)	0.70417 (0.69436, 0.71398)	✓
Contemp. crosscor. GDP-Inflation	0.37143 (0.36749, 0.37537)	0.36614 (0.35782, 0.37447)	✓

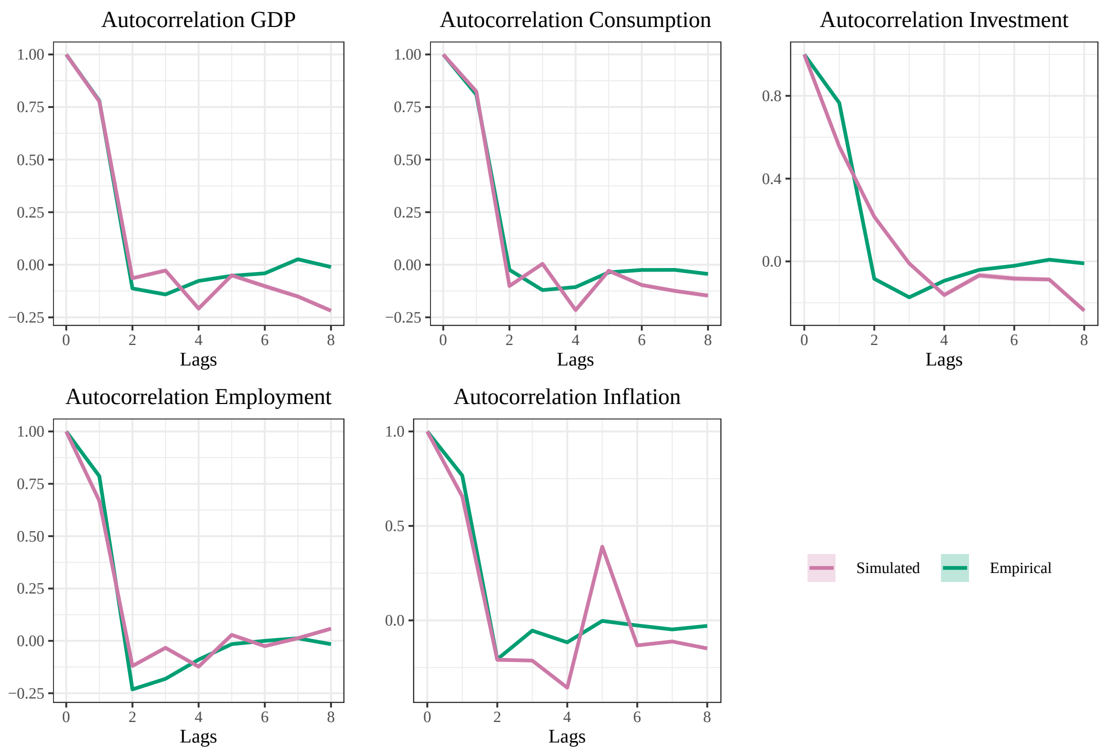

Figure A1: Autocorrelation functions for the main macroeconomic variables. Functions are constructed from empirical and simulated data to which the Hamilton filter has been applied. Lines for simulated data represent averages across 108 model simulations with different, reproducible seeds. Bands (too narrow to be visible) represent 95% confidence intervals.

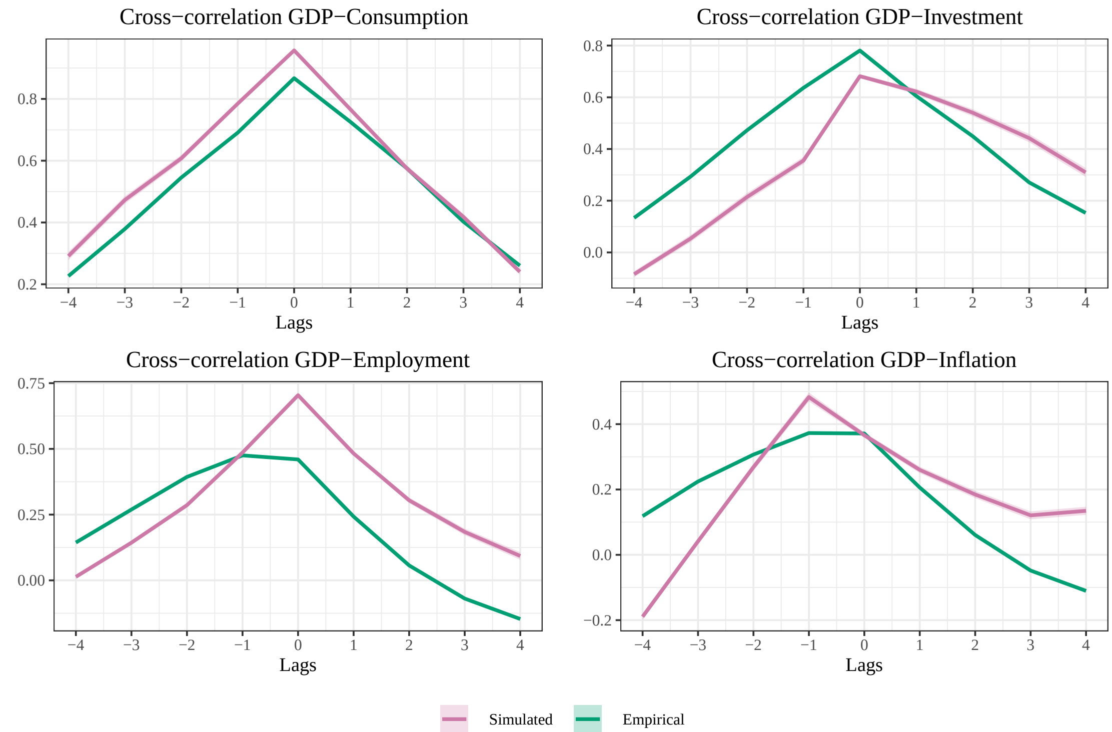

Figure A2: Cross-correlation functions for the main macroeconomic variables. Functions are constructed from empirical and simulated data to which the Hamilton filter has been applied. Lines for simulated data represent averages across 108 model simulations with different, reproducible seeds. Bands (too narrow to be visible) represent 95% confidence intervals.

Turning to long-run statistics, table A5 compares the growth rates of real GDP, carbon emissions and energy use in industry taken from SSP data and IAM scenarios to those produced by the calibrated DSK-SFC model. The table shows that the simulated growth rates are all very close to the target values, with real GDP growing at an annual rate of around 1.2% and both emissions and energy use being almost constant.

Next, we take a look at some qualitative characteristics of the simulated data. Figures A3 and A4 make use of the stock-flow consistent accounting structure of the model to plot the sectoral net worths and sectoral financial balances as ratios of GDP. This is done to ensure that none of the ratios exhibits a persistent long-run trend. Finally, table A6 provides a list of qualitative stylised facts which are reproduced by the calibrated DSK-SFC model, along with references for each of them.

Table A5: Comparison of SSP/IAM scenario and DSK-SFC growth rates. Simulated numbers represent averages across 108 model simulations with different, reproducible seeds. Numbers in parentheses give 95% confidence intervals

Description	**SSP/IAM**	**DSK-SFC**
Av. annual GDP growth	0.01233	0.01188 (0.01173, 0.01204)
Av. annual carbon emissions growth	0.00032	-0.00009 (-0.00031, 0.00014)
Av. annual growth of energy use in industry	0.00022	0.00014 (-0.00009, 0.00036)

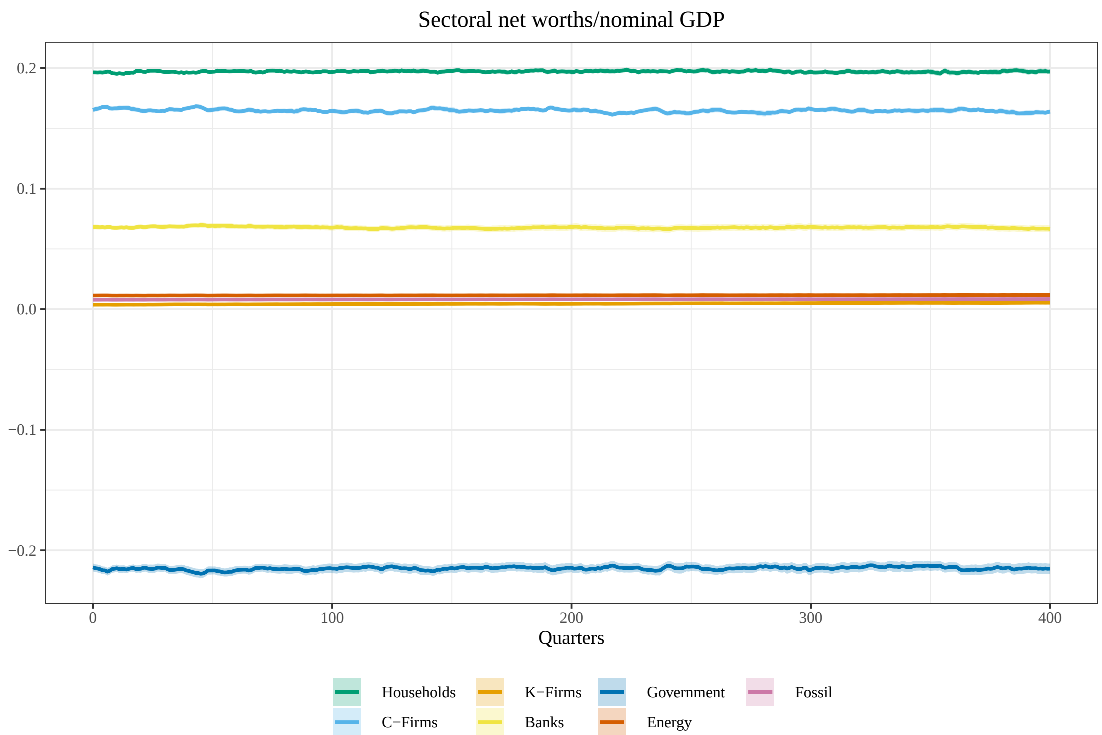

Figure A3: Simulated sectoral financial balances as ratios of quarterly nominal GDP. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands represent 95% confidence intervals.

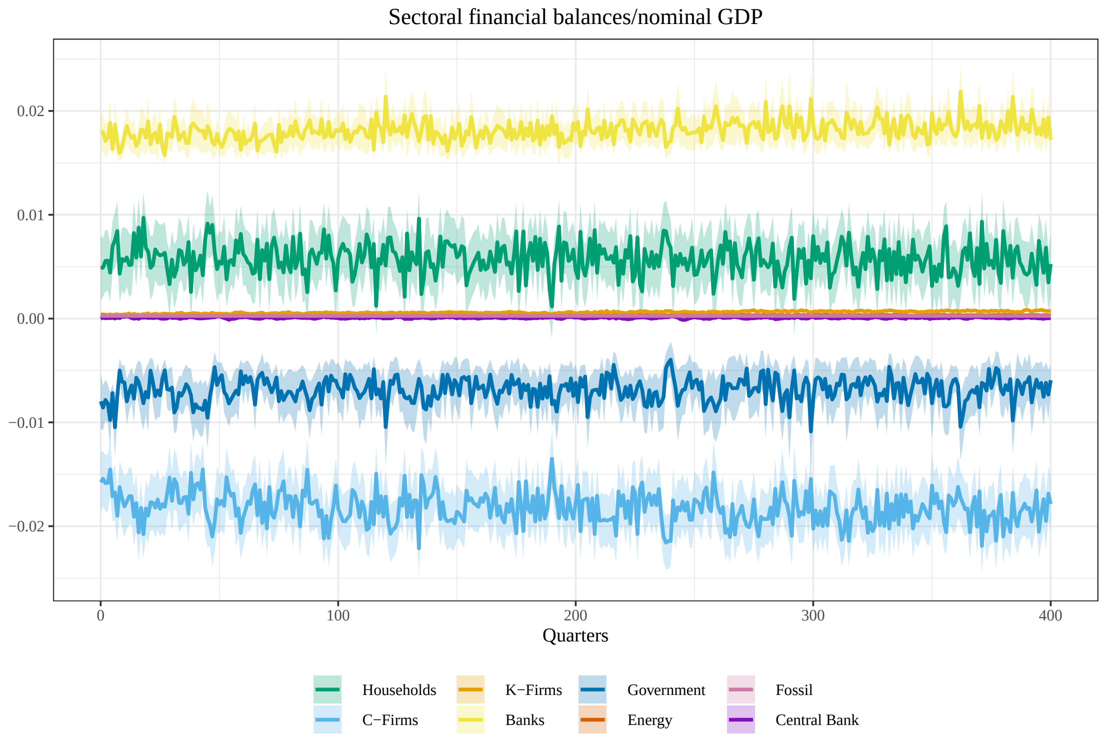

Figure A4: Simulated sectoral net worths as ratios of annualised nominal GDP. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands represent 95% confidence intervals.

Table A6: Qualitative stylised facts reproduced by DSK-SFC

Stylised fact	**Reference(s)**
Endogenous growth with persistent fluctuations	Burns and Mitchell (1946); Kuznets (1966); Zarnowitz (1985); Stock and Watson (1999)
Fat-tailed GDP growth-rate distribution	Fagiolo et al. (2008); Castaldi and Dosi (2009); Lamperti and Mattei (2018)
Relative volatility of main macroeconomic aggregates	Stock and Watson (1999); Napoletano et al. (2006)
Cross-correlations of main macroeconomic aggregates	Stock and Watson (1999); Napoletano et al. (2006)
Pro-cyclical private sector debt	Lown and Morgan (2006)
Pro-cyclical R&D investment	Wälde and Woitek (2004)
Pro-cyclical energy demand	Moosa (2000)

Table A6 – continued from previous page

Stylised fact	Reference(s)
Pro-cyclical emissions	Doda (2014)
Cross-correlation between private sector debt and loan losses	Foos et al. (2010); Mendoza and Terrones (2012)
Fat-tailed firm growth-rate distribution	Bottazzi and Secchi (2003, 2006)
Lumpy investment rates at firm level	Doms and Dunne (1998)
Persistent productivity heterogeneity across firms	Bartelsman and Doms (2000); Dosi (2007)
Persistent energy efficiency heterogeneity across firms	DeCanio and Watkins (1998); Petrick (2013)
Persistent emission intensity heterogeneity across firms	Petrick (2013)

Appendix B Additional results

The scenarios compared in the main body of the paper focused on the role of policy intervention and the sensitivity of the nominal wage rate to inflation, while keeping the upward and downward pass-through rates of energy cost increases to final selling prices at their empirically calibrated values (100% upward and 60% downward). The scenarios shown in this appendix explore the implications of allowing for different pass-through rates, in the absence of policy intervention. In addition, we examine how well the *"EU 2022 policy mix"* scenario discussed in the main body of the paper matches macroeconomic data for the EU27 since the onset of the energy crisis.

B.1 The role of different symmetric pass-through rates

We compare several scenarios with different pass-through rates and no policy intervention, assuming that downward pass-through rates are identical to upward ones. Such an experiment can be thought of either as an outcome of market competition, or the result of a policy measure encouraging or mandating certain pricing behaviours.

An upward pass-through rate of 100% implies that firms pass on the entirety of the increase in the energy price to their selling prices; similarly, a downward pass-through rate of 100% means that the subsequent energy price decrease is also fully reflected in selling prices. At the opposite extreme, 0% upward and downward pass-through rates imply that selling prices do not at all react to changes in energy cost as a consequence of the shock, with all changes being instead absorbed by firms' mark-up rates. We also examine intermediate cases in which only a part of the energy cost increase and subsequent decrease is reflected in final output prices. In contrast to the results shown in the main body of the paper which used empirically calibrated upward (100%) and downward (60%) pass-through rates we assume *symmetric* upward and downward pass-through rates, here.

This implies that the energy price shock has no long-term impact on functional distribution since firm mark-up rates always remain at or eventually return to their pre-shock levels.

Figure B1 shows that different pass-through rates have a limited impact on firm balance sheets in terms of debt defaults and bankruptcies. As discussed in the main body of the paper, when firms collectively pass on the entirety of the energy cost increase, this exacerbates the collapse in real aggregate demand, meaning that firms are not able to capture the profit volumes necessary to avoid an increase in loan defaults and bankruptcies, even leading the bad debt to nominal GDP ratio to peak at a value slightly (but not significantly) higher than in the case in which firms do not pass on the energy cost increase. By contrast, lower pass-through rates reduce the impact of the shock on final output prices and hence real demand for consumption goods, but lead firms to decrease investment due to a decrease in their profit margins and willingness to borrow. While lower pass-through rates lead to a somewhat milder recession, economic losses are still substantial in all cases.

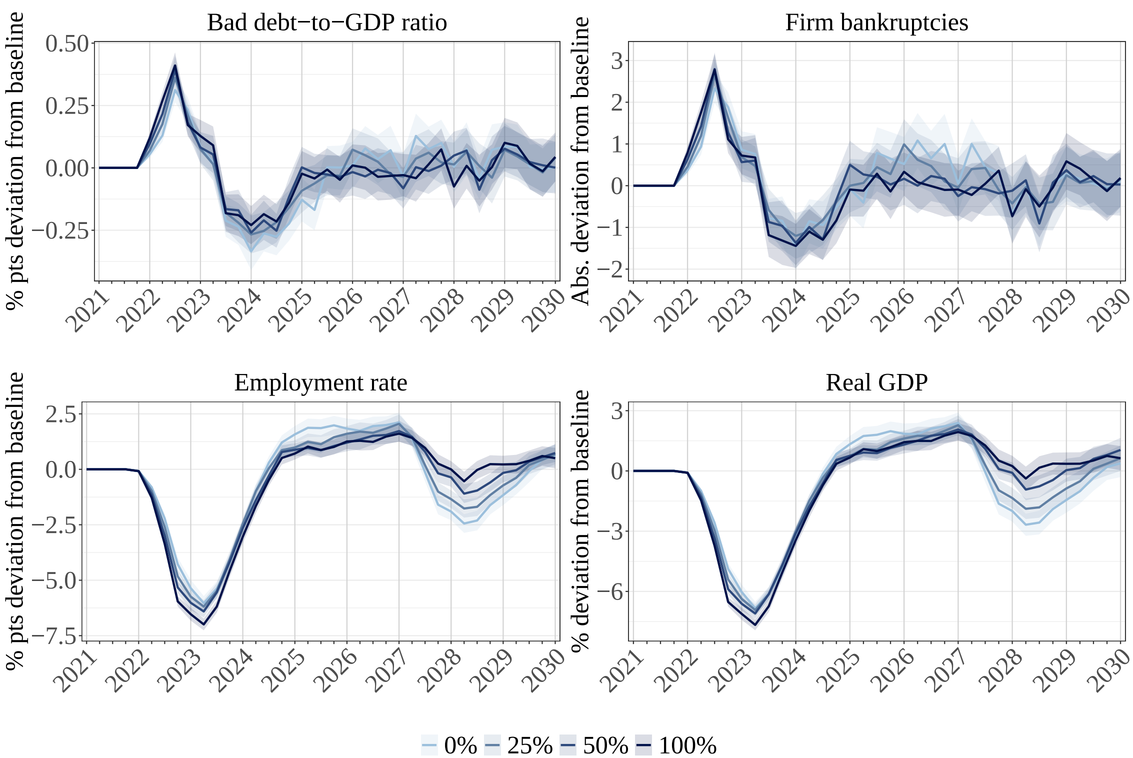

Figure B1: Ratio of bad firm bad debt to nominal GDP (top left), number of firm failures (top right), employment rate (bottom left), and real GDP (bottom right), for various symmetric pass-through rates. Time-series are shown as absolute or percent deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

Figure B2 shows that pass-through rates are an important determinant of the consequences of the shock for functional distribution. Lower pass-through rates limit the decline in the wage share at the expense of the firm profit share and vice-versa. As indicated above, the assumption of symmetric pass-through rates implies that functional distribution tends back to the baseline composition in the medium to long run.

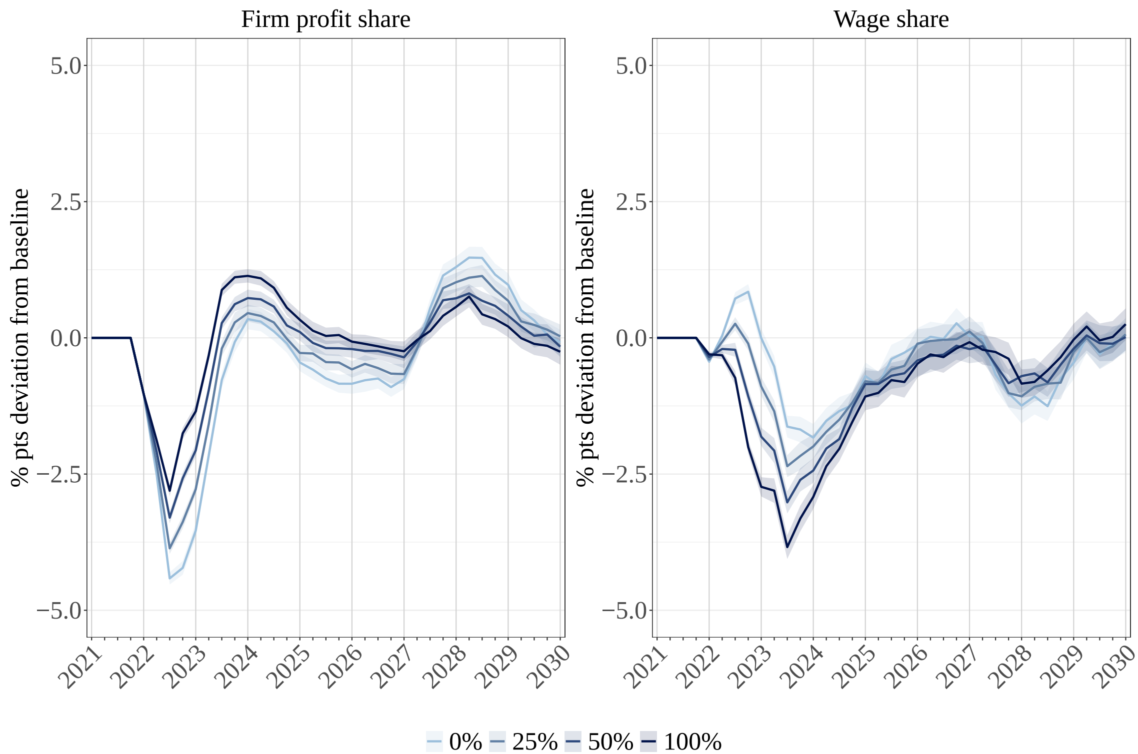

Figure B2: Wage and firm income shares for various symmetric pass-through rates. Time-series are shown as absolute deviations from the baseline run without a shock to the fossil fuel price. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals.

As shown in Figure B3, in cases of incomplete upward pass-through, declines in firm mark-ups partly or wholly offset the effects of energy cost increases on CPI inflation. In these cases mark-ups subsequently recover as energy costs recede, leading to elevated levels of inflation during the recovery phase.

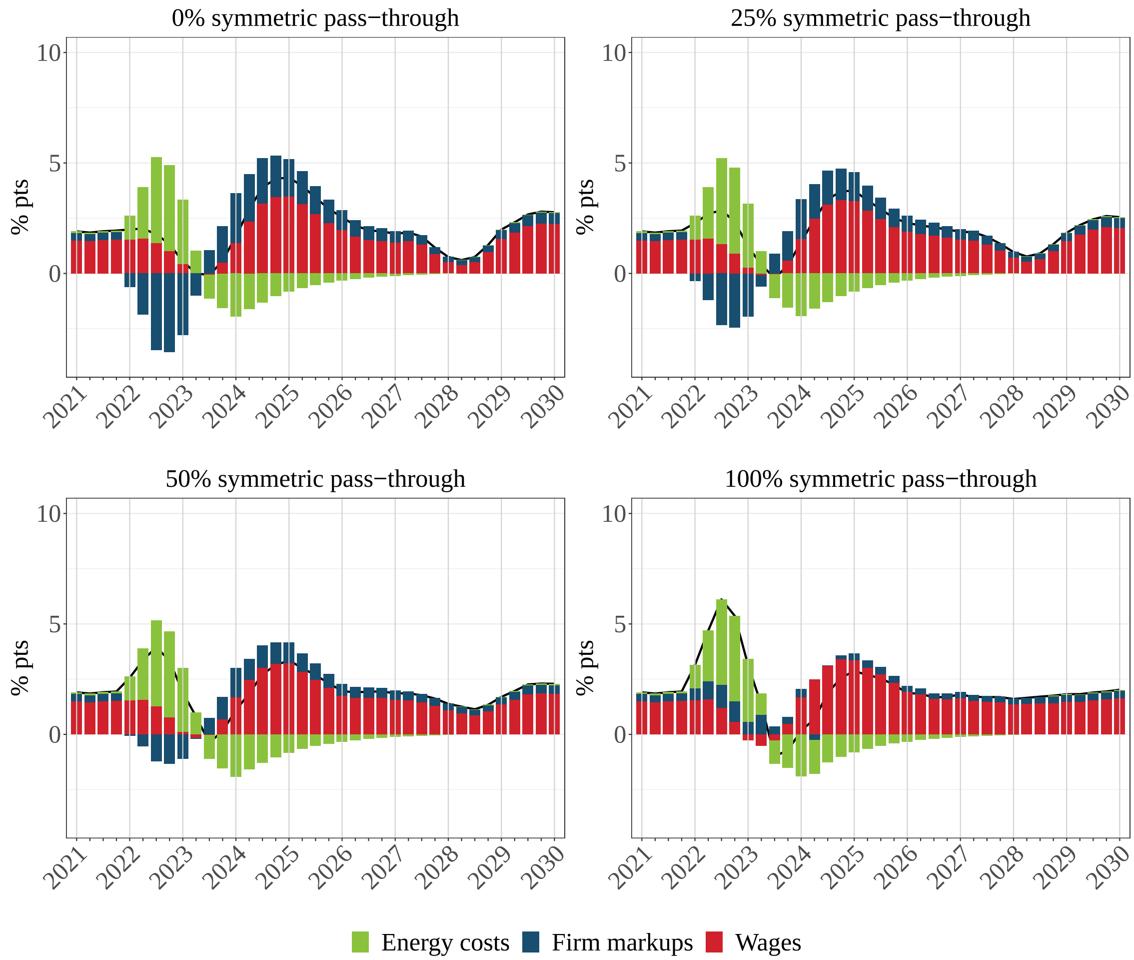

Figure B3: Year-on-year CPI inflation decomposition for various symmetric pass-through rates. Numbers are averages across 108 model simulations with different, reproducible seeds. Black line represents CPI inflation rate.

B.2 Comparison with empirical post-shock data

To further evaluate the performance of our model in addition to the validation exercises provided in Appendix A, we compare its behaviour under the fossil fuel price shock to empirical macroeconomic post-shock data for the EU27 available at the time of writing. All empirical time-series are taken from Eurostat. To ease comparability, we normalise all empirical time-series to be equal to their simulated counterparts in 2021 Q3 and assess how well the model reproduces their subsequent evolution, focusing in particular on the performance of our empirically calibrated policy scenario (in which 80% of transfer payments are targeted to households and 20% to firms). Below, we provide plots showing the empirical and simulated dynamics of inflation (see Figure B4), the employment rate (see Figure B5), real GDP (see Figure B6), and real consumption (see Figure B7).

While the *EU 2022 policy mix* scenario generally does quite well in matching empirical dynamics, we do observe some significant gaps between empirical and simulated data. In particular, the model under-estimates the peak of the inflation rate by a rather substantial margin and predicts slightly lower values for GDP and the employment rate. However, it should be noted that the simulated values for GDP and employment in particular are within a reasonable range compared to the empirical ones when factoring in confidence intervals, and our model realistically reproduces the qualitative dynamics of these variables.

The quantitative gaps may be explained by two limitations of the model and our scenarios. Firstly, we do not depict the full battery of support policies which have been implemented in the European Union and instead focus purely on transfer payments, while in the real world, other measures such as direct energy price controls and subsidies have also been implemented.

Secondly, regarding the inflation rate in particular, our model and scenarios do not take into account the supply chain disruptions which have affected the European economy in the aftermath of the Covid-19 pandemic and which contributed to heightened inflationary pressures even prior to the Russian invasion of Ukraine. This, however, is also a deliberate choice, as the present work seeks to isolate the effect of energy price shocks in particular.

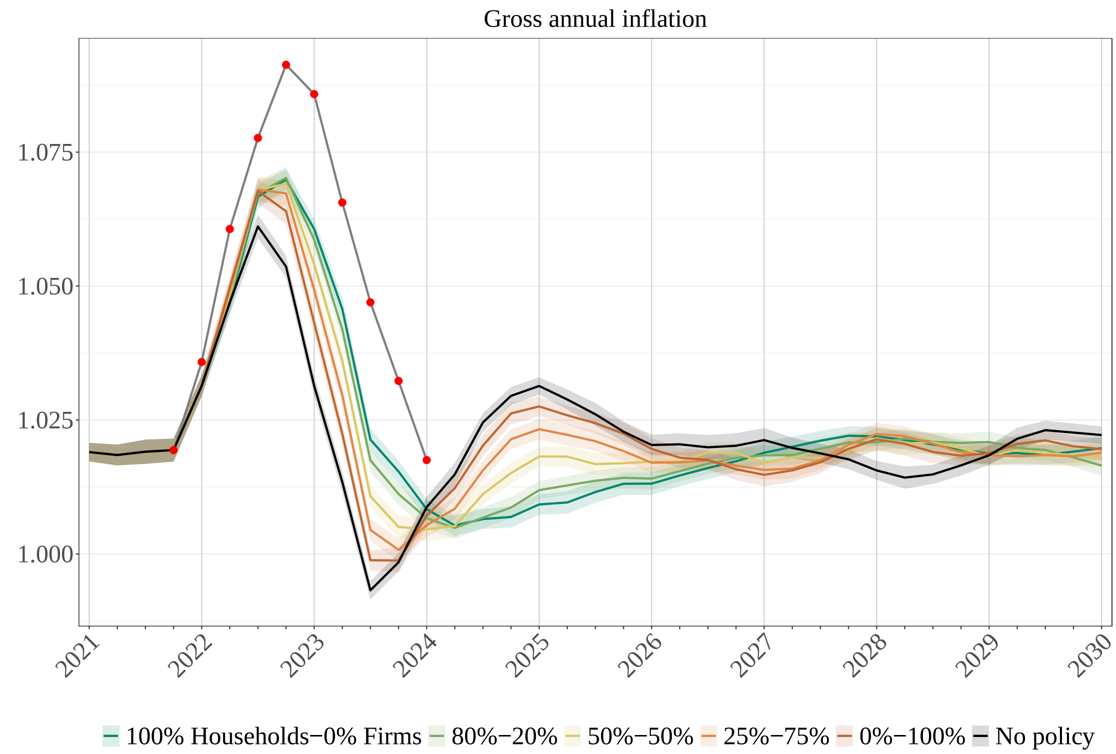

Figure B4: Year-on-year gross CPI inflation. Time-series are shown in levels for different distributions of transfer payments between households and firms. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals. Red dots represent empirical post-shock data, normalised such that the value in 2021Q3 is identical to its simulated counterpart.

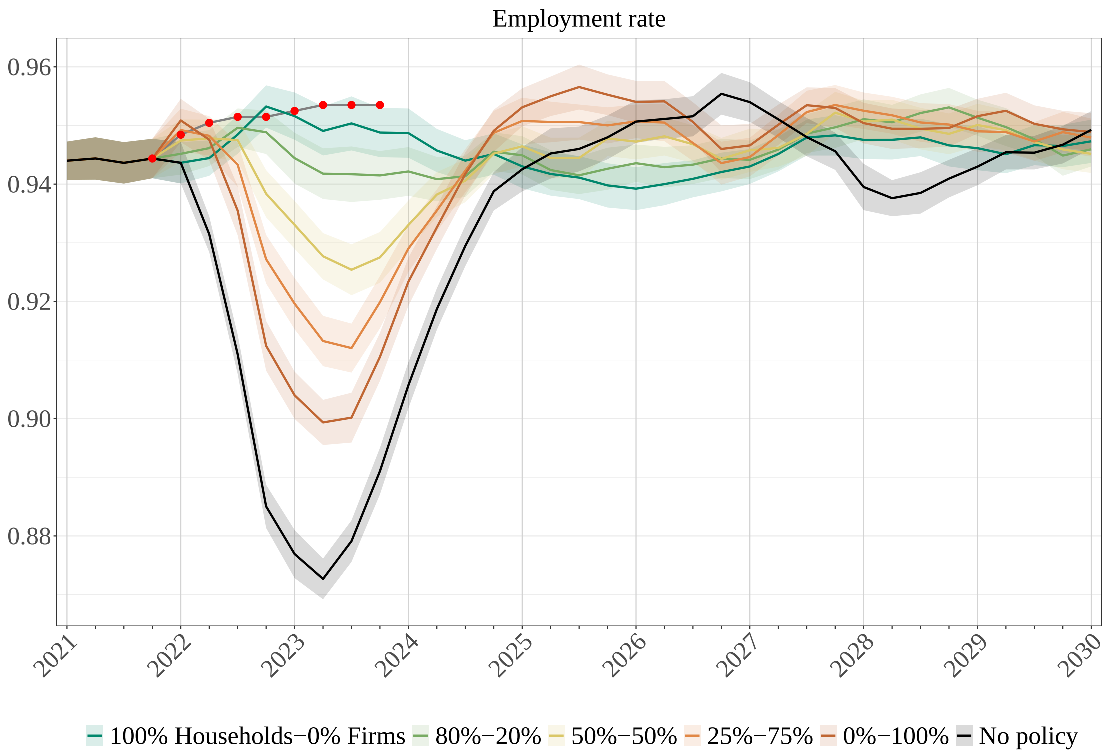

Figure B5: Employment rate. Time-series are shown in levels for different distributions of transfer payments between households and firms. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals. Red dots represent empirical post-shock data scaled such that the value in 2021Q3 is the same as the value simulated just before the shock is triggered.

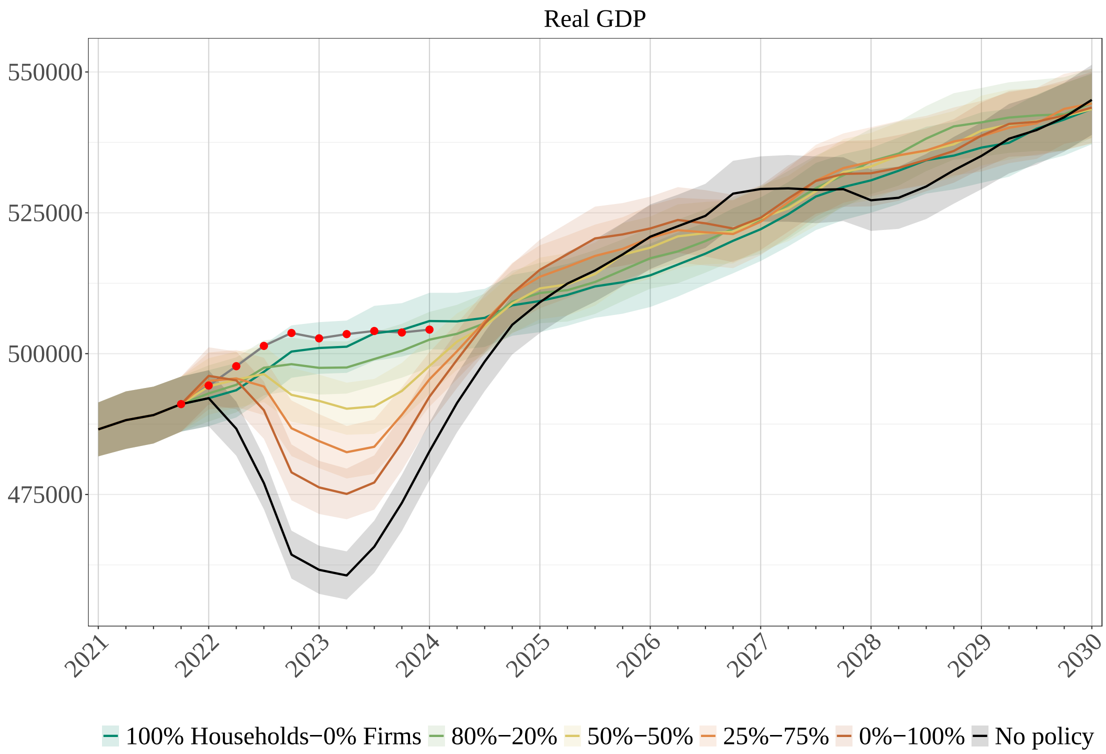

Figure B6: Real GDP. Time-series are shown in levels for different distributions of transfer payments between households and firms. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals. Red dots represent empirical post-shock data, normalised such that the value in 2021Q3 is identical to its simulated counterpart.

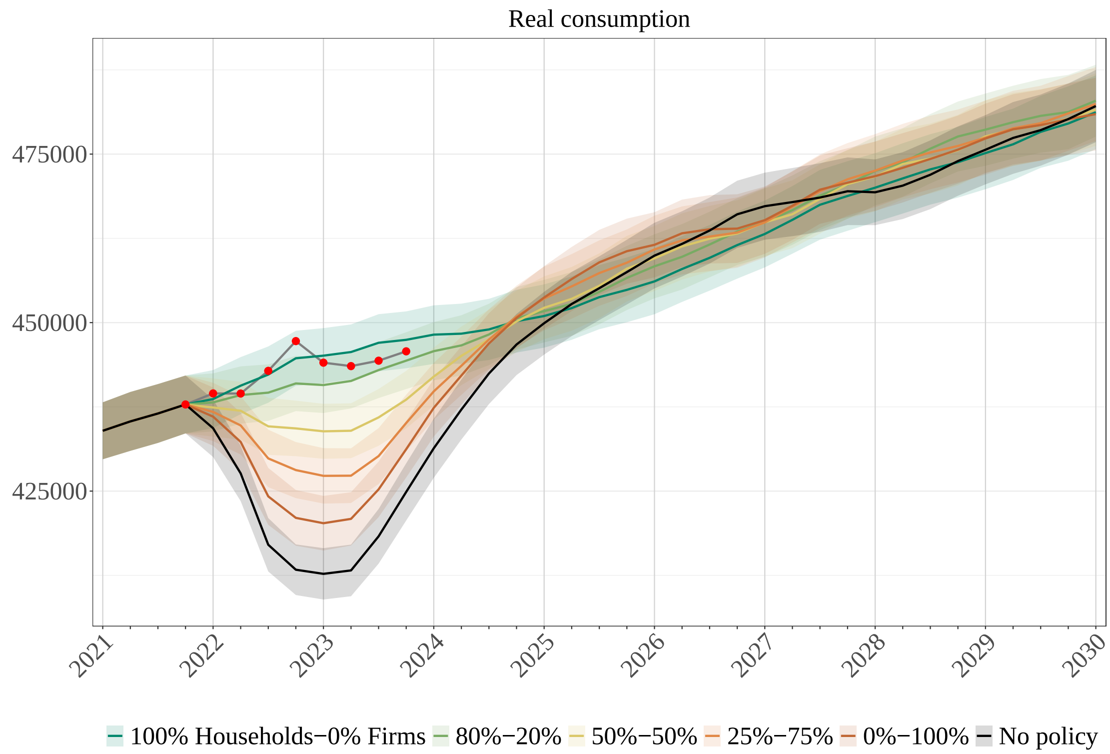

Figure B7: Real consumption. Time-series are shown in levels for different distributions of transfer payments between households and firms. Lines represent averages across 108 model simulations with different, reproducible seeds. Bands are 95% confidence intervals. Red dots represent empirical post-shock data, normalised such that the value in 2021Q3 is identical to its simulated counterpart.

Appendix C Full model description

This appendix provides a full description of the DSK-SFC model as applied in the main body of the paper. It is a lightly modified version of the detailed model description contained in Reissl et al. (2024). The interested reader is referred to the aforementioned paper for more in-depth discussions and justifications of behavioural assumptions.

Tables C1 and C show the balance sheet and transaction flow matrices of the DSK-SFC model, illustrating the model's sectoral structure, the composition of sectoral balance sheets, and the inter-sectoral transactions depicted.

Table C1: Balance Sheet Matrix

	Households	**C-Firms**	**K-Firms**	**Banks**	**Gov.**	**CB**	**Energy**	**Fossil**	Σ
Bank Deposits	$+D_h$	$+D_c$	$+D_k$	$-D$			$+D_e$		0
Gov. Bonds				$+GB_b$	$-GB$	$+GB_{cb}$			0
Loans		$-L$		$+L$					0
CB Reserves				$+R_b$		$-R$		$+R_f$	0
CB Advances				$-A$		$+A$			0
Fixed Capital		$+K$					$+K_e$		$K + K_e$
Σ	NW_h	NW_c	NW_k	NW_b	NW_g	NW_{cb}	NW_e	NW_f	$K + K_e$

Table C2: Transactions Flow Matrix

	Households	**C-Firms**	**K-Firms**	**Banks**	**Government**	**Central Bank**	**Energy**	**Fossil**	Σ
Consumption	$-C$	$+C$							0
Investment		$-I$	$+I$						0
Benefits	$+G$				$-G$				0
Taxes		$-Tax_c$	$-Tax_k$	$-Tax_b$	$+Tax$		$-Tax_e$		0
Wages	$+W$	$-W_c$	$-W_k$				$-W_e$		0
Fuel							$-FF$	$+FF$	0
Energy		$-E_c$	$-E_k$				$+E$		0
Dividends	$+Div$	$-Div_c$	$-Div_k$	$-Div_b$			$-Div_e$	$-Div_f$	0
Interest Loans		$-iL$		$+iL$					0
Int. Gov. Bonds				$+iGB_b$	$-iGB$	$+iGB_{cb}$			0
Int. Advances				$-iA$		$+iA$			0
Transfer CB					$+T_{cb}$	$-T_{cb}$			0
Transfer Entry	$-T_h$	$+T_c$	$+T_k$	$-T_b$	$-T_g$				0
Bailout				$+Bail$	$-Bail$				0
Saving	(Sav_h)	(Sav_c)	(Sav_k)	(Sav_b)	(Sav_g)	(Sav_{cb})	(Sav_e)	(Sav_f)	0
Δ Deposits	$-\Delta D_h$	$-\Delta D_c$	$-\Delta D_k$	$+\Delta D$			$-\Delta D_e$		0
Δ Gov. Bonds				$-\Delta GB_b$	$+\Delta GB$	$-\Delta GB_{cb}$			0
Δ Loans		$+(\Delta L)$		$-(\Delta L)$					0
Δ Reserves				$-\Delta R_b$		$+\Delta R$		$-\Delta R_f$	0
Δ Advances				$+\Delta A$		$-\Delta A$			0
Σ	0	0	0	0	0	0	0	0	

The remainder of this appendix is structured as follows:

- Section C.1 contains the sequence of events
- Section C.2 describes the household sector
- Section C.3 describes the K-Firm sector
- Section C.4 describes the C-Firm sector
- Section C.5 describes the firm exit and replacement mechanisms
- Section C.6 describes the banking sector
- Section C.7 describes the government
- Section C.8 describes the central bank
- Section C.9 describes the energy sector
- Section C.10 describes the climate module

C.1 Sequence of events

In every simulation period, the following sequence of events takes place:

1. In every 4th simulation period (i.e. every year), the carbon tax rate charged to the energy sector is updated.
2. C-Firms receive capital goods ordered in the previous period.
3. C-Firms and K-Firms calculate unit cost and set their prices for the current period.
4. Banks determine the maximum amount of credit they are prepared to extend.
5. Banks set the loan interest rates charged to individual customers.
6. K-Firms send brochures to attract new clients.
7. C-Firms calculate expected demand and desired production.
8. C-Firms earmark worn-out and technologically obsolete machines for scrapping.
9. C-Firms set a desired capital stock and desired expansion investment.
10. C-Firms calculate effective production cost.

11. C-Firms determine internal financing and the maximum amount they are willing to borrow. If necessary, desired investment is scaled back; the cost of desired investment is calculated.

12. Bank credit is allocated to C-Firms, which scale back investment and possibly production if credit-rationed. Firms which are unable to roll over existing loans become inactive and are prepared for exit.

13. C-Firms and K-Firms calculate the labour input required for production.

14. Total labour demand is calculated; if total labour demand exceeds the maximum labour supply, C-Firm and K-Firm production is scaled back.

15. The unemployment rate and consequent unemployment benefit payments are calculated.

16. Production takes place. Total energy demand and emissions from industry are calculated.

17. Expansion investment, R&D, and energy production take place in the Energy sector.

18. C-Firms pay for investment.

19. C-Firms, K-Firms and the Energy sector pay wages; the Government pays unemployment benefits.

20. Machines are scrapped.

21. C-Firms' competitiveness and ex-ante market shares are calculated. C-Firms with very low market share become inactive and are prepared for exit.

22. K-Firm profit is calculated. K-Firms pay energy, taxes, and dividends. K-Firms which are unable to make energy payments become inactive and are prepared for exit.

23. Households calculate desired consumption.

24. Consumption expenditure is allocated to C-Firms.

25. K-Firm and C-Firms' profits are calculated.

26. C-Firms pay energy, loan service and taxes. C-Firms unable to pay for energy or loan service become inactive and are prepared for exit. C-Firms with negative equity become inactive and are prepared for exit.

27. Energy sector profits are calculated. The Energy sector pays fossil fuel input and taxes. The Fossil Fuel sector makes transfer/dividend payments to the households.

28. Macroeconomic aggregates and averages are computed.

29. The nominal wage rate is updated.
30. Exiting C-Firms and K-Firms are replaced by new entrants.
31. Bank profits are calculated. Banks pay taxes and dividends.
32. Banks with negative equity are bailed out by the Government.
33. The Government budget is calculated. Deficits are covered by bonds sold to Banks and the Central Bank.
34. The Central Bank sets the policy interest rate for the following period.
35. Net inflows and outflows of reserves are calculated for Banks; if necessary, Banks take advances from the Central Bank.
36. Endogenous technological change takes place in the K-Firm sector.
37. In every 4th simulation period (i.e. every year), the climate module is updated using emissions from the current period.
38. The fossil fuel price and the mark-up in the energy sector are re-set for the next period. If an energy price shock takes place in the next period, the respective variables are set to their shocked values.

C.2 Households

The household sector is modelled as an aggregate entity with three sources of income: wage payments W_t, dividend payments Div_{t-1} (consisting of dividends from consumption good firms, capital good firms, the energy sector, banks, and the fossil fuel sector), and unemployment benefits UB_t. Households do not pay taxes in the calibration used in this paper, making the disposable income of the sector:

$$YD_t = W_t + Div_{t-1} + UB_t \tag{C.1}$$

Households will supply any amount of labour demanded at the current nominal wage rate w_t up to a maximum LS_t, which represents the current aggregate labour force and which changes at an exogenous rate, $LS_t = \big(1+g_L\big)LS_{t-1}$. The amount of labour actually employed, L_t, depends on the labour demand of firms and the energy sector as described below. Labour income is then given by $W_t = w_t L_t$. Households receive an unemployment benefit payment given by $UB_t = \zeta w_t \big(LS_t - L_t\big)$, where ζ is the replacement rate.

Households' desired nominal consumption expenditure is given by

$$\begin{aligned} C_{d,t} =& \alpha_1 \big(W_t + UB_t\big) + \alpha_2 \big(Div_{t-1}\big) \\ &+ \alpha_3 D_{h,t-1} \end{aligned} \tag{C.2}$$

where $D_{h,t-1}$ is the stock of previously accumulated bank deposits held by households. Households hence have different propensities to consume out of wage and benefit income (α_1), dividend income (α_2) and accumulated wealth (α_3).[11] The actual consumption expenditure of households, C_t, is determined by households' interaction with consumption good firms described below. In addition to consumption, households also make transfer payments T_h to firms in order to finance firm entry as described below. Household saving accumulates in the form of bank deposits, $D_{h,t}$. The rule used to distribute this aggregate quantity of deposits among individual banks is described in Section C.6.

At the end of a period t, the uniform nominal wage rate to be paid in $t+1$, is set. It is given by

$$w_{t+1} = \big(1 + \mathfrak{w}_t\big) w_t \tag{C.3}$$

$$\mathfrak{w}_t = min\Big(\overline{\mathfrak{w}}, max\Big(-\overline{\mathfrak{w}}, \pi^* + \psi_1 \widehat{\pi}_t + \psi_2 \widehat{Pr}_t - \psi_3 \widehat{U}_t\Big)\Big) \tag{C.4}$$

where:

- $\overline{\mathfrak{w}}$ is an exogenous parameter limiting period-by-period variations in the wage rate
- π^* is the central bank's fixed inflation target
- $\widehat{\pi}_t$ is the deviation of the current consumer price inflation rate from the inflation target
- $\widehat{Pr}_t$ is a weighted average of current and past percentage changes in the average labour productivity across firms (which, as described below, depends on the combination of vintages of capital goods owned by consumption good producers and the heterogeneous production techniques of capital goods producers).[12]
- $\widehat{U}_t$ is the change in the unemployment rate relative to $t-1$

[11] It is assumed that households cannot borrow for consumption, meaning that if desired consumption is greater than the stock of deposits currently held by households, desired consumption is reduced to the maximum amount which can be financed out of deposits.

[12] This is computed as $\widehat{Pr}_t = \eta \widehat{Pr}_{t-1} + (1-\eta)\frac{\overline{Pr}_t - \overline{Pr}_{t-1}}{\overline{Pr}_{t-1}}$ where $\overline{Pr}_t$ is the average labour productivity across C-Firms and K-Firms.

C.3 Capital good firms

The sector of capital goods firms (K-Firms) consists of $N1$ individual firms, indexed by k, where $k = 1, ..., N1$. Each firm produces a capital good with unique characteristics, using a unique production technique (both of which evolve due to endogenous technological change) with labour and energy as inputs. K-firms compete on quality and price.

C.3.1 Production and labour demand

While at any given point in time, each K-firm produces one single 'vintage' of capital good, technological progress leads to the continuous emergence of new capital good vintages. A generic vintage is denoted using κ and is defined by the triple $\Sigma_\kappa = \left(Pr_\kappa, EE_\kappa, EF_\kappa\right)$, indicating, respectively, the embedded labour productivity, energy efficiency, and environmental friendliness (i.e. the amount of emissions generated per unit of energy used) implied by using a capital good of that vintage κ in the production of consumption goods. An existing unit of capital good/machine is defined by its vintage, i.e. Σ_κ, its age, i.e. how many periods have elapsed since its production, and its maximum lifespan. When the age of a machine exceeds $\aleph^K$, the machine can no longer be used in production. $\aleph^K$ is constant and homogeneous across machines.

In addition to producing capital goods with heterogeneous characteristics, K-firms also use heterogeneous production techniques. These are defined by the triple $\Sigma_k = \left(Pr_{k,t}, EE_{k,t}, EF_{k,t}\right)$, indicating, respectively, the labour productivity, energy efficiency, and environmental friendliness of a generic K-firm production process. Note that production techniques are also subject to technological innovation, hence they change over time.

K-firms produce on demand, i.e., they receive orders from clients in period t, produce all ordered machines in t, and deliver to clients in $t + 1$. This implies that K-firms do not accumulate inventories, neither planned nor otherwise.

Once orders have been received, K-Firm labour demand is computed:

$$L^d_{k,t} = \frac{Q_{k,t}}{Pr_{k,t}} \tag{C.5}$$

Where $Q_{k,t}$ is the quantity of machines ordered from k.

Similarly, k's demand for energy is given by:

$$En^d_{k,t} = \frac{Q_{k,t}}{EE_{k,t}} \tag{C.6}$$

Production generates emissions, which we assume to be proportional to the amount of energy required in production:

$$Em_{k,t} = \frac{EF_{k,t}}{EE_{k,t}} Q_{k,t} \tag{C.7}$$

C.3.2 Capital good market dynamics

K-firms set prices by applying a fixed and homogeneous markup, μ^K, over unit cost of production. For a generic K-firm, unit cost of production is given by:

$$uc_{k,t} = \frac{w_t}{Pr_{k,t}} + \frac{p_{e,t-1}}{EE_{k,t}} \tag{C.8}$$

Where w_t is the nominal wage, $Pr_{k,t}$ is the labour productivity of k's production process, $p_{e,t}$ is the price of energy and $EE_{k,t}$ is the energy efficiency. The price charged by a generic K-firm can thus be written as:

$$p_{k,t} = \big(1 + \mu^K\big) uc_{k,t} \tag{C.9}$$

Each K-firm is endowed with an equal number of C-Firm clients at the beginning of a simulation. During the simulation, K-firms compete in order to increase their market share by sending brochures to potential new clients. Brochures contain information regarding the current vintage sold by a K-Firm, Σ_κ, as well as the price charged, $p_{k,t}$. The number of brochures sent by a K-Firm k is proportional to its size in terms of the number of existing clients:

$$BROCH_{k,t} = max\Bigg(1, \lfloor \Gamma CLNT_{k,t-1} \rceil\Bigg) \tag{C.10}$$

$BROCH_{k,t}$ is the number of brochures sent by k, $CLNT_{k,t}$ is the number of k's current clients, and Γ is an exogenous parameter. Brochures are sent to randomly drawn firms from the full set of C-Firms. Each C-Firm compares the received brochures and chooses as its preferred supplier taking into account both the price charged per unit of capital good and the unit cost of production implied by using the vintage (this choice is described in detail in Section C.4.2 below).

C.3.3 Technological change

K-firms aim to improve their production technique Σ_k and the technology embedded in the capital vintage they produce, Σ_κ. In order to do so, they engage in technological innovation and imitation through research and development (R&D).

We assume a two-step process of technological change. First, K-Firms allocate resources for innovation and imitation. The size of these R&D investments determines the likelihood of innovation and/or imitation being successful. Conditional on innovation and/or imitation being successful, the characteristics of the resulting technology or technologies are determined stochastically. The innovating/imitating firm then determines whether a new technology is superior to the existing one and adopts it if this is the case.

The overall amount of resources which a K-Firm k wishes to devote to R&D is given by a fraction $\mathfrak{o}$ of its current revenue if k's current revenue is positive,[13] and equal to the resources devoted in the previous period otherwise:

$$RD_{k,t} = \begin{cases} \mathfrak{o} Sales_{k,t} & \text{If} \quad Sales_{k,t} > 0 \\ RD_{k,t-1} & \text{Otherwise} \end{cases} \tag{C.11}$$

$\mathfrak{o}$ is fixed and homogeneous across K-Firms. R&D activities are performed using labour as an input. Consequently, a K-Firm's demand for labour for R&D is given by

$$L^{rd}_{k,t} = \frac{RD_{k,t}}{w_t} \tag{C.12}$$

We assume that K-Firms' demand for labour used for R&D is never rationed.[14] The hired labour is subsequently divided between R&D activity devoted to innovation $\left(RD^{in}_{k,t}\right)$ and imitation $\left(RD^{im}_{k,t}\right)$:

$$\begin{aligned} RD^{in}_{k,t} &= \mathfrak{x}^K L^{rd}_{k,t} \\ RD^{im}_{k,t} &= \left(1 - \mathfrak{x}^K\right) L^{rd}_{k,t} \end{aligned} \tag{C.13}$$

$\mathfrak{x}^K$ is fixed and homogeneous across K-Firms. The model then determines whether a K-Firm k is successful in imitating and/or innovating a technology in period t. The probability of innovating/imitating is increasing in the respective R&D input:

$$\begin{aligned} P(Innovate)_{k,t} &= 1 - exp\left(-\mathfrak{b}^K_1 RD^{in}_{k,t}\right) \\ P(Imitate)_{k,t} &= 1 - exp\left(-\mathfrak{b}^K_2 RD^{im}_{k,t}\right) \end{aligned} \tag{C.14}$$

$\mathfrak{b}^K_1$ and $\mathfrak{b}^K_2$ are fixed and homogeneous across K-Firms. For each K-Firm k, two draws from a Bernoulli distribution are made. The first takes the value 1 with probability $P(innovate)_{k,t}$, and if this is the case, the firm k innovates. Similarly, the second takes the value 1 with probability $P(imitate)_{k,t}$, and if this is the case, the firm k imitates. Note that this implies that a K-Firm can both innovate a new technology and imitate the technology of a competitor in the same period. As described below, the technology actually adopted then depends on their respective characteristics.

If a K-Firm innovates, the characteristics of the new technology are determined stochastically. Recall that at each point in time, every K-Firm produces a single, unique vintage of capital good κ, characterised by the triple $\Sigma_\kappa = \left(Pr_\kappa, EE_\kappa, EF_\kappa\right)$ denoting the labour productivity, energy efficiency and environmental friendliness implied by using this vintage of capital good in the production of consumption goods. In addition, each K-Firm has an individual technique for producing

[13] Since not all C-Firms invest in every period, an individual K-Firm with few customers may have zero sales in a period.

[14] If overall labour demand exceeds the size of the labour force, LS_t, only production activity is scaled back until aggregate labour demand equals the size of the labour force.

capital goods, defined by the triple $\Sigma_k = \left(Pr_{k,t}, EE_{k,t}, EF_{k,t}\right)$, denoting the labour productivity, energy efficiency and environmental friendliness of the production process. Innovation in the model is depicted as a random simultaneous change to all the components of Σ_κ and Σ_k, resulting in a new vintage of capital good κ_{in} and an associated technique for producing this type of capital good. In particular, the characteristics of κ_{in} are given by:

$$\begin{aligned} Pr_{\kappa_{in}} &= \left(1+\mathfrak{I}_{1,k,t}\right)Pr_\kappa \\ EE_{\kappa_{in}} &= \left(1+\mathfrak{I}_{2,k,t}\right)EE_\kappa \\ EF_{\kappa_{in}} &= \left(1-\mathfrak{I}_{3,k,t}\right)EF_\kappa \end{aligned} \tag{C.15}$$

where:

- $\mathfrak{I}_{1,k,t}$ is a draw from a beta distribution with shape parameters $\mathfrak{b}_3^K$ and $\mathfrak{b}_4^K$, rescaled on the interval $\left(\mathfrak{b}_5^K, \mathfrak{b}_6^K\right)$.

- $\mathfrak{I}_{2,k,t}$ is a draw from a beta distribution with shape parameters $\mathfrak{b}_7^K$ and $\mathfrak{b}_8^K$, rescaled on the interval $\left(\mathfrak{b}_9^K, \mathfrak{b}_{10}^K\right)$.

- $\mathfrak{I}_{3,k,t}$ is a draw from a beta distribution with shape parameters $\mathfrak{b}_{11}^K$ and $\mathfrak{b}_{12}^K$, rescaled on the interval $\left(\mathfrak{b}_{13}^K, \mathfrak{b}_{14}^K\right)$.

Similarly, the production technique used to produce the innovated vintage κ_{in} is given by

$$\begin{aligned} Pr_{in,k,t} &= \left(1+\mathfrak{I}_{4,k,t}\right)Pr_{k,t} \\ EE_{in,k,t} &= \left(1+\mathfrak{I}_{5,k,t}\right)EE_{k,t} \\ EF_{in,k,t} &= \left(1-\mathfrak{I}_{6,k,t}\right)EF_{k,t} \end{aligned} \tag{C.16}$$

where:

- $\mathfrak{I}_{4,k,t}$ is a draw from a beta distribution with shape parameters $\mathfrak{b}_{15}^K$ and $\mathfrak{b}_{16}^K$, rescaled on the interval $\left(\mathfrak{b}_{17}^K, \mathfrak{b}_{18}^K\right)$.

- $\mathfrak{I}_{5,k,t}$ is a draw from a beta distribution with shape parameters $\mathfrak{b}_{19}^K$ and $\mathfrak{b}_{20}^K$, rescaled on the interval $\left(\mathfrak{b}_{21}^K, \mathfrak{b}_{22}^K\right)$.

- $\mathfrak{I}_{6,k,t}$ is a draw from a beta distribution with shape parameters $\mathfrak{b}_{23}^K$ and $\mathfrak{b}_{24}^K$, rescaled on the interval $\left(\mathfrak{b}_{25}^K, \mathfrak{b}_{26}^K\right)$.

Note that the support of the various Beta distributions need not be confined to positive values (and indeed this is not the case in the calibration used in the main paper). This implies that the firm may discover a new capital vintage or production technique which is inferior to the current one along one or multiple dimensions. This modelling choice mimics the trial and error process characterizing technological change.

Imitation, by contrast, is based on a measure of the technological proximity between two K-Firms. If a K-Firm k successfully imitates, the model computes the technological proximity between k and every other K-Firm j, comparing both the production techniques of k and j and the vintages κ and κ_{im} produced by k and j respectively:

$$\begin{aligned}
Dist^1_{k,j,t} &= \left(Pr_\kappa - Pr_{\kappa_{im}}\right)^2 \\
Dist^2_{k,j,t} &= \left(EE_\kappa - EE_{\kappa_{im}}\right)^2 \\
Dist^3_{k,j,t} &= \left(EF_\kappa - EF_{\kappa_{im}}\right)^2 \\
Dist^4_{k,j,t} &= \left(Pr_{k,t} - Pr_{\kappa_{j,t}}\right)^2 \\
Dist^5_{k,j,t} &= \left(EE_{k,t} - EE_{\kappa_{j,t}}\right)^2 \\
Dist^6_{k,j,t} &= \left(EF_{k,t} - EF_{\kappa_{j,t}}\right)^2 \\
Prox_{k,j,t} &= \frac{1}{\sqrt{\sum_{i=1}^{6} Dist^i_{k,j,t}}}
\end{aligned} \tag{C.17}$$

The proximity measures are then normalised by dividing them by the sum of all proximity measures. They are then placed on the interval $[0,1]$ by iterating over all proximities and, for each j, modifying them to $Prox_{k,j,t} = Prox_{k,j,t} + Prox_{k,j-1,t}$. Next, a uniform random number ε is drawn. Firm k will imitate the technology of firm j if $\varepsilon \leq Prox_{k,j,t}$ and $\varepsilon > Prox_{k,j-1,t}$. This ensures that K-Firms are more likely to imitate the technology of competitors with a higher technological proximity. Note that the firm may imitate a technology which is inferior to its current one along one or multiple dimensions.

The final step in the process of endogenous technological change concerns the adoption decision. Recall that a new technology discovered by some K-Firm k may be inferior to the one currently used by k along one or more dimensions. Similarly, firm k may end up imitating a technology which is inferior along one or more dimensions. To decide which new technology (if any) to adopt, the firm compares the innovated and imitated technologies to one another, as well as to its existing technology. To do so, it uses the same rule which C-Firms use in choosing their capital goods supplier and in deciding whether an existing machine should be replaced with a more modern one (see Section C.4). In particular, k computes a measure of vintage attractiveness for its existing technology as well as the innovated and imitated technologies:

$$\begin{aligned}
A_{\kappa,t} &= p_{k,t} + uc_{\kappa,t} b \\
A_{\kappa_{in},t} &= p_{in,k,t} + uc_{\kappa_{in},t} b \\
A_{\kappa_{im},t} &= p_{im,k,t} + uc_{\kappa_{im},t} b
\end{aligned} \tag{C.18}$$

$p_{k,t}$ is the price which k currently charges for one unit of the capital good, computed as described in equations (C.8) and (C.9). $p_{in,k,t}$ and $p_{im,k,t}$ are the prices which k would charge when using the innovated and imitated capital good production techniques, respectively. The uc terms denote the unit cost of producing one unit of the consumption good using a machine of the current (κ), innovated $\left(\kappa_{in}\right)$ and imitated $\left(\kappa_{im}\right)$ vintages, respectively. b is a fixed and homogeneous payback parameter.[15] The K-Firm then chooses the technology for which A takes the lowest value, i.e. that with best trade-off between price and quality. Note that a technology does not have to be superior along all dimensions in order to be adopted/retained by a K-Firm. Additionally, both the unit cost of producing a capital good of some innovated vintage and the unit cost of using that vintage in the production of consumption goods are functions of the wage rate and the energy price. A higher energy price may hence, for instance, induce K-Firms to more readily adopt technologies with a higher energy efficiency even if they are more costly along other dimensions (e.g. implying a higher labour input).

C.3.4 Profits and dividends

Once all K-Firm decisions and market interactions have taken place, gross profits can be computed: sales enter the profit calculation with a positive sign; the wage and energy bills enter the profit calculation with a negative sign.

$$\Pi_{k,t}^{gross} = Sales_{k,t} - W_{k,t} - En_{k,t} \tag{C.19}$$

where:

$$\begin{aligned} Sales_{k,t} &= p_{k,t} Q_{k,t} \\ W_{k,t} &= w_t L_{k,t} + w_{t-1} * L_{k,t-1}^{rd} \\ En_{k,t} &= p_{e,t} En_{k,t}^{d} \end{aligned} \tag{C.20}$$

- $Sales_{k,t} \equiv$ nominal sales; $p_{k,t} \equiv$ price; $Q_{k,t} \equiv$ number of machines sold;
- $W_{k,t} \equiv$ wage bill; $w_t \equiv$ nominal wage; $L_{k,t} \equiv$ quantity of labour employed in production; $L_{k,t-1}^{rd} \equiv$ quantity of labour employed for R&D in $t-1$;
- $En_{k,t} \equiv$ energy bill; $p_{e,t} \equiv$ energy price; $En_{k,t}^{d} \equiv$ energy demand;

If gross profits are positive, K-Firms pay profit taxes, which are charged at a flat rate τ^K:

$$\Pi_{k,t}^{net} = \left(1 - \mathbf{1}^{\left[\Pi_{k,t}^{gross} > 0\right]} \tau^K\right) \Pi_{k,t}^{gross} \tag{C.21}$$

[15] b is defined in terms of units of consumption goods and gives the number of units of consumption good which must be produced using a superior technology (i.e. one offering a lower unit cost of production) to justify investing in it.

Where $\mathbf{1}^{[\Pi_{k,t}^{gross}>0]}$ is an indicator function taking the value 1 if $\Pi_{k,t}^{gross} > 0$ and 0 otherwise. If profits are positive, firms pay dividends, $Div_{k,t}$ to households:

$$Div_{k,t} = \mathbf{1}^{[\Pi_{k,t}^{net}>0]}\delta^K \Pi_{k,t}^{net} \tag{C.22}$$

where δ^K is the dividend payout rate, which is assumed to be constant and homogeneous across K-firms. Retained earnings are held in the form of unremunerated bank deposits, and we assume that K-Firms cannot borrow from the banking sector.

C.3.5 Failure and exit

K-Firms may exit the model and be replaced by new ones for two reasons. First, a K-Firm will exit if it loses all of its customers, i.e. if all C-Firms for which it was the preferred supplier of capital goods switch to a different supplier. Second, a K-Firm will exit if it is unable to meet payments for energy input or wages. Recall that K-Firms produce on demand and price their output at a mark-up over unit cost. In addition, as described below, C-Firms only invest if they are certain that they can pay for the capital goods ordered. However, while the current wage rate is known when unit cost is computed, the current price of energy is not, and hence its lagged value is used by K-Firms when setting prices. This means that an increase in the energy price may lead to one or more K-Firms being unable to (fully) pay for energy used as an input in production. In addition, wages for R&D paid in t are based on the amount of resources devoted to R&D in $t-1$. Hence, a situation may arise in which a K-Firm is unable to fully cover current production cost in addition to paying wages for R&D labour from the previous period. In these cases, a failing K-Firm will still produce the capital goods ordered by its customers in the current period but then exit the market after satisfying as many of its payment obligations as possible using all funds it still has available. The replacement of exiting K-Firms is described in Section C.5.

C.4 Consumption good firms

The model includes a consumption good sector consisting of $N2$ individual firms, each indexed as c, where $c = 1, ..., N2$. Each firm produces a homogeneous final consumption good using capital, labour, and energy as inputs. Production techniques are heterogeneous across C-Firms in terms of productivity, energy efficiency, and environmental friendliness due to the composition of the capital stock of each C-firm being different in terms of vintages (see also Section C.3). C-Firms compete in the consumption goods market in order to capture as large a market share as possible. Since consumption goods are homogeneous, competition takes place along the dimensions of price and firms' ability to deliver the quantity demanded.

C.4.1 Desired production

C-Firms' desired production is set to match expected demand and achieve desired inventory holdings. The latter are kept in order to enable the firm to serve demand exceeding expectations. Actual production may fall short of desired production if a C-Firm is capital or labour-constrained or if it cannot finance the desired production. The desired production is determined as

$$Q^d_{c,t} = Dem^e_{c,t} \tag{C.23}$$

Where $Q^d_{c,t}$ is desired production and $Dem^e_{c,t}$ is expected demand, which is assumed to be adaptive, i.e.:

$$Dem^e_{c,t} = \sigma Dem_{c,t-1} + (1-\sigma) Dem^e_{c,t-1} \tag{C.24}$$

Where $Dem_{c,t-1}$ is the actual demand received by c in the previous period and σ is an exogenous parameter that is homogeneous across C-Firms.

As indicated above, actual production $Q_{c,t}$ may differ from desired production if c has an insufficient stock of machines to carry out desired production, if c is constrained by labour availability, or if c cannot finance the desired level of production. In a first step, c checks whether its productive capacity in terms of available machine tools is sufficient to carry out its desired production. While, as outlined above, machine vintages differ in terms of labour productivity, energy efficiency and environmental friendliness, it is assumed that every machine can produce a maximum of $\mathfrak{Q}$ units of output when used at full capacity. $\mathfrak{Q}$ is constant and homogeneous across vintages. If the desired output of c exceeds its maximum productive capacity, c's desired output is scaled back to the maximum producible given its capital stock.

C.4.2 Investment

As described in Section C.3, C-Firms choose their current supplier of capital goods by comparing brochures which specify the characteristics and prices of capital good vintages. C-Firms compute a measure of vintage attractiveness $A_{\kappa,t}$ for each observed vintage κ:

$$A_{\kappa,t} = p_{k,t} + uc_{\kappa,t} b \tag{C.25}$$

Where $p_{k,t}$ is the price charged by the K-Firm k which produces the vintage κ, $uc_{\kappa,t}$ is the unit cost of production implied by using vintage κ in the production of consumption goods, and b is a payback parameter. Note that this equation is identical to the one used by K-Firms in deciding whether or not to adopt an innovated/imitated technology. Each firm chooses the observed supplier whose offering implies the lowest $A_{\kappa,t}$.

We distinguish between two types of investment in capital goods: one is aimed at maintaining or expanding productive capacity in order to meet expected future production needs, the other is replacement investment and is aimed at substituting still usable but technologically obsolete machines with new ones situated at the technological frontier.

C-Firms aim to attain a given level of capacity utilization $u < 1$, which is fixed and homogeneous across firms. Desired productive capacity, $\mathfrak{K}^d_{c,t}$, can therefore be written as:

$$\mathfrak{K}^d_{c,t} = \frac{Q^d_{c,t}}{u} \tag{C.26}$$

Desired expansion investment is set to achieve $\mathfrak{K}^d_{c,t}$. Expansion investment is constrained by an exogenous maximum level of addition to productive capacity achievable in a single period, which in turn defines a maximum productive capacity achievable through expansion investment, $\overline{\mathfrak{K}}_{c,t}$. In addition, while consumption goods are assumed to be perfectly divisible, only integer units of capital goods can be purchased. Desired expansion investment is hence given by

$$EI^d_{c,t} = max\left(0, \left\lfloor \frac{min\left(\overline{\mathfrak{K}}_{c,t}, \mathfrak{K}^d_{c,t}\right) - \mathfrak{K}^s_{c,t}}{\mathfrak{Q}} \right\rfloor \mathfrak{Q}\right) \tag{C.27}$$

Where $\mathfrak{K}^s_{c,t}$ is c's current productive capacity from which machines reaching their maximum age in t (which the firm knows with certainty will be scrapped at the end of t) have already been removed. $\overline{\mathfrak{K}}_{c,t}$ is defined as:

$$\overline{\mathfrak{K}}_{c,t} = \left\lceil \frac{(1+\lambda)\mathfrak{K}_{c,t}}{\mathfrak{Q}} \right\rceil \mathfrak{Q} \tag{C.28}$$

Where λ is a homogeneous parameter.

Besides expansion investment, which covers both the replacement of machines which have reached their maximum age and the expansion of productive capacity, a C-Firm may also wish to substitute machines which have not reached their maximum age if they have become technologically obsolete *vis-a-vis* the vintage offered by its capital goods supplier. Machines owned by C-Firm c of some vintage κ are compared to the vintage currently offered by c's supplier of capital goods, κ^*, which is the most advanced technology known to c. c's machines of vintage κ are deemed to be technologically obsolete if:

$$\frac{p_{\kappa^*,t}}{uc_{\kappa,t} - uc_{\kappa^*,t}} \leq b \tag{C.29}$$

Where $p_{\kappa^*,t}$ is the price charged by c's current capital good supplier for the vintage κ^* and b is the same payback parameter also used in equations (C.25) and (C.18). $uc_{\kappa,t}$ is the current unit cost of production implied by the use of vintage κ, while $uc_{\kappa^*,t}$ is the corresponding unit cost arising from the use of κ^*. If vintage κ is deemed obsolete, firm c wishes to replace its entire stock of machines of vintage κ with machines of vintage κ^*. This comparison takes place in every period for all vintages currently operated by c. Unlike expansion investment, there is no exogenous constraint on the amount of substitution investment which can be carried out within a single period. Capital goods ordered by C-Firms in t, both for expansion and substitution investment, are delivered at the beginning of $t+1$. The nominal value of capital goods on C-Firms' balance sheets is given by their price at the time of purchase and subsequently remains constant until they are scrapped.

Consumption firms may reduce desired investment due to financial considerations. If the the nominal value of desired investment exceeds the sum of internal funds and the maximum amount of credit a firm is willing to take up after paying for production cost (see Section C.4.4), investment demand is reduced until it equals the amount of remaining potential liquidity. In addition, C-Firms may be constrained on the credit market if banks are not willing lend as much as C-Firms demand, in which case investment (and potentially also current production) will be (further) reduced.

C.4.3 Pricing and production costs

C-Firms set individual prices by applying a markup over unit cost of production:

$$p_{c,t} = \big(1 + \mu_{c,t}\big) uc_{c,t} \tag{C.30}$$

Where $p_{c,t}$ is the price, $\mu_{c,t}$ is the mark-up and $uc_{c,t}$ is the unit cost of production (see below).

The markup evolves following a simple adaptive rule: when its market share grows, C-Firm c revises its markup upward, and vice-versa.

$$\mu_{c,t} = \begin{cases} \mu_{c,t-1}\left[1 + \Delta^{\mu}\widehat{f_{c,t-1}}\right] & \text{if } f_{c,t-2} > 0 \\ \mu_{c,t-1} & \text{Otherwise} \end{cases} \tag{C.31}$$

Where $f_{c,t}$ is c's market share in the market for consumption goods at time t, Δ^{μ} is an exogenous parameter that is homogeneous across C-Firms and $\widehat{f_{c,t-1}} = \frac{f_{c,t-1} - f_{c,t-2}}{f_{c,t-2}}$. If the mark-up resulting from equation (C.31) is negative, it is set to zero instead.

The unit cost of production, $uc_{c,t}$, entering Equation (C.30) depends on the composition of c's capital stock. Recall that each capital vintage κ of which c currently owns one or more units implies a certain unique unit cost when used to produce consumption goods. $uc_{c,t}$ is hence a weighted average across all κ-specific unit costs of production, with the weights being given by the share of machine tools of each vintage κ in the capital stock of c. We can therefore compactly express $uc_{c,t}$ as:

$$uc_{c,t} = \sum_{\kappa \in \Phi_{\kappa,c,t}} uc_{\kappa,t} \frac{\mathfrak{K}_{\kappa,c,t}}{\mathfrak{K}_{c,t}} \tag{C.32}$$

Where κ is a generic capital vintage, $\Phi_{\kappa,c,t}$ is the set of vintages available to firm c, $uc_{\kappa,t}$ is the unit cost of production embedded in vintage κ, and $\mathfrak{K}_{\kappa,c,t}$ is the amount of production that firm c can achieve using technology κ. Note that $\frac{\mathfrak{K}_{\kappa,c,t}}{\mathfrak{K}_{c,t}}$ represents the weight applied to each vintage κ.

If the capacity utilisation implied by c's desired production is smaller than 1, c will use the most efficient combination of capital vintages allowing it to produce the desired level of output, meaning that its effective unit cost will differ from $uc_{c,t}$. Capital vintages are ranked according to their unit cost of production, from the lowest to the highest. Beginning from the most cost-efficient vintage, c activates machines until the desired scale of production has been reached, with all remaining capacity remaining idle. We can therefore write effective unit cost as

$$uc^e_{c,t} = \sum_{\kappa \in \Phi^u_{\kappa,c,t}} uc_{\kappa,t} \frac{\mathfrak{K}_{\kappa,c,t}}{\mathfrak{K}^u_{c,t}} \tag{C.33}$$

where $\Phi^u_{\kappa,c,t}$ denotes the subset of vintages available to firm c which is actually used in production in period t and $\mathfrak{K}^u_{c,t}$ denotes the part of the capital stock of c actually used in t.

Finally, the unit cost of production associated with a particular vintage κ, $uc_{\kappa,t}$, is given by the sum of labour cost and energy cost:

$$uc_{\kappa,t} = \frac{w_t}{Pr_\kappa} + \frac{p_{e,t-1}}{EE_\kappa} \tag{C.34}$$

Where w_t is the nominal wage, Pr_κ is the vintage-specific labour productivity, $p_{e,t}$ is the price of energy and EE_κ is the vintage-specific energy efficiency.

By the same logic as Equation (C.33), we can write c's effective labour productivity, energy efficiency, and environmental friendliness as:

$$\begin{aligned} Pr^e_{c,t} &= \sum_{\kappa \in \Phi^u_{\kappa,c,t}} Pr_{\kappa,t} \frac{\mathfrak{K}_{\kappa,c,t}}{\mathfrak{K}^u_{c,t}} \\ EE^e_{c,t} &= \sum_{\kappa \in \Phi^u_{\kappa,c,t}} EE_{\kappa,t} \frac{\mathfrak{K}_{\kappa,c,t}}{\mathfrak{K}^u_{c,t}} \\ EF^e_{c,t} &= \sum_{\kappa \in \Phi^u_{\kappa,c,t}} EF_{\kappa,t} \frac{\mathfrak{K}_{\kappa,c,t}}{\mathfrak{K}^u_{c,t}} \end{aligned} \tag{C.35}$$

Using the effective labour productivity computed as shown above, C-Firms then calculate their labour demand as

$$L^d_{c,t} = \frac{Q^d_{c,t}}{Pr^e_{c,t}} \tag{C.36}$$

Similarly, c's demand for energy can be calculated as

$$En^d_{c,t} = \frac{Q^d_{c,t}}{EE^e_{c,t}} \tag{C.37}$$

Productive activity also generates emissions, which we assume to be proportional to the amount of energy input required for production:

$$Em_{c,t} = \frac{EF^e_{c,t}}{EE^e_{c,t}} Q^d_{c,t} \tag{C.38}$$

Note that the quantities calculated above are computed using the desired production of c, $Q^d_{c,t}$. As outlined below, actual output may be lower than desired output if c is unable to hire a sufficient amount of labour or if c cannot fully finance its desired production. In these cases, labour demand, energy demand and emissions are adjusted accordingly.

C.4.4 Credit

Besides possibly being credit-rationed by its bank (see Section C.6), each C-Firm c has an internal constraint in the form of a maximum increase in the amount of credit that it is willing to take up for the purpose of investment. In the first instance, C-Firms aim to finance investment in capital goods out of previously accumulated internal funds in the form of bank deposits, $D_{c,t}$. If the latter are insufficient, they plan to take out additional loans up to a maximum given by a fixed and homogeneous multiple ϕ of previous revenue from sales of consumption goods net of production cost (wages and energy payments), $NR_{c,t-1}$. In addition, they take into account that outstanding loans, $\mathfrak{l}_{c,t-1}$, need to be rolled over and prospective production costs, $-uc^e_{c,t}Q^d_{c,t}$, need to be covered. The maximum amount of funds which is expected to be available for financing investment is hence given by:

$$F^{max}_{c,t} = max\big(0, D_{c,t} + \phi NR_{c,t-1} - \mathfrak{l}_{c,t-1} - uc^e_{c,t}Q^d_{c,t}\big) \tag{C.39}$$

If $F^{max}_{c,t}$ is insufficient to finance desired investment, C-Firms first curtail substitution investment aimed at the replacement of functional but technologically obsolete machines, and subsequently also expansion investment aimed at the replacement of machines which have reached their maximum age and at the expansion of productive capacity.

In addition, a C-Firm may also face an external financing constraint if its bank is not willing to extend as much credit as the firm demands (see Section C.6). In this case some planned expenditures must be (further) reduced. We assume a ranking of expenditures, whereby expenditures are sequentially reduced, up to the point at which the remaining activities can be financed. For this purpose, the C-Firm's expenditures are reduced in the following order:

1. Substitution investment due to technological obsolescence is reduced to 0

2. Expansion investment (including replacement of machines which have reached their maximum age) is reduced to 0

3. Production is scaled down until production costs can be met

If, following this process, available funds are still insufficient to roll over outstanding debt and finance a positive level of current production, the affected C-Firm does not produce any output and exits the market.

C.4.5 Competitiveness

Since households are presently depicted as an aggregate entity, their demand for consumption goods is also an aggregate quantity. This aggregate demand is distributed across C-firms by applying a quasi-replicator equation to determine the market share of each firm.

The process of consumption good market competition is split into two separate steps: First, a measure of competitiveness $E_{c,t}$ is computed for each C-Firm c. Second, this measure is used to update the market shares and distribute aggregate consumption demand across C-Firms. Competitiveness is defined as

$$E_{c,t} = -\left(\frac{p_{c,t}}{\widehat{p}_t}\right)^{\omega_1} - \left(\frac{l_{c,t}}{\widehat{l}_t}\right)^{\omega_2} \tag{C.40}$$

Where $p_{c,t}$ is the price charged by firm c, whereas $\widehat{p}$ is the average price across the whole consumption good sector. l^t is the level of demand which c left unsatisfied in the previous period (computed as shown in Section C.4.6), with $\widehat{l}_t$ being the respective average across all C-Firms. ω_1 and ω_2 are exogenous parameters giving the relative importance of price and ability to fill demand in determining competitiveness. $E_{c,t}$ is then used in order to update the ex-ante share of aggregate consumption demand accruing to each individual C-Firm:

$$\tilde{f}_{c,t} = f_{c,t-1}\left(\frac{2\omega_3}{1+e^{\left(-\chi\frac{E_{c,t}-\widehat{E}_t}{\widehat{E}_t}\right)}} + (1-\omega_3)\right) \tag{C.41}$$

Where $\tilde{f}_{c,t}$ and $f_{c,t-1}$ are the ex-ante and lagged market shares of c respectively and $\widehat{E}_t$ is a weighted average of $E_{c,t}$, computed using $f_{c,t-1}$ as weights. χ and ω_3 are exogenous parameters. Note that the functional form chosen for Equation (C.41) implies that period-to-period percent changes in $f_{c,t}$ must fall within $\pm\omega_3$. The ex-ante market shares of C-Firms which have already failed prior to the determination of market shares due to inability to finance their productive activities are re-set to zero. In addition, we assume that firms for whom $\tilde{f}_{c,t}$ becomes smaller than a lower threshold $\mathfrak{f}$ exit and their market shares are re-set to zero.

Note that Equation (C.41) does not ensure that the ex-ante market shares sum to 1. The model therefore applies the following adjustment in order to normalise them:

$$f_{c,t} = \frac{\tilde{f}_{c,t}}{\sum_{i=1}^{N2} \tilde{f}_{i,t}} \tag{C.42}$$

C.4.6 Consumption good market

Following the determination of ex-ante market shares, the distribution of households' consumption demand among C-Firms takes place. This distribution takes place over multiple rounds. In the first round, the consumption demand received by an individual C-Firm c is given by

$$Dem^1_{c,t} = \frac{C_{d,t}}{cpi_t} f_{c,t} \tag{C.43}$$

where $C_{d,t}$ is households' aggregate nominal consumption demand and cpi_t is a consumption price index computed using the market shares $f_{c,t}$ as weights. Given the demand received by c in the first round, two cases can result:

1. $Dem^1_{c,t} \leq Q_{c,t}$, i.e. the quantity produced by c is greater than the demand received in the first round. In this case, the current revenue of c, which is initialised to zero, is augmented by $Dem^1_{c,t} p_{c,t}$. $l_{c,t}$, which quantifies C-Firms' ability to meet demand, is set to 1. The quantity of goods produced by c still for sale in future rounds is set to $Q_{c,t} - Dem^1_{c,t}$. The market share of c for the second round is left unchanged; $f^2_{c,t} = f_{c,t}$.

2. $Dem^1_{c,t} > Q_{c,t}$, meaning that c cannot satisfy the demand received in the first round. In this case, the current revenue of c is augmented by $Q_{c,t} p_{c,t}$. $l_{c,t}$ is set to $1 + Dem^1_{c,t} - Q_{c,t}$. The quantity of goods produced by c still for sale in future rounds is set to zero. The market share of c for the second round set to zero; $f^2_{c,t} = 0$.

In both cases, $Dem_{c,t}$, which will enter into the determination of expected demand in $t+1$, and which is initialised to zero, is augmented by $Dem^1_{c,t}$.

Following this first round of distribution of consumption demand, households' nominal consumption demand is reduced by the sum of sales which have taken place in the first round. Second round market shares (which have been set to zero for C-Firms which have already sold all that they have produced) are normalised again:

$$f^2_{c,t} = \frac{f^2_{c,t}}{\sum_{i=1}^{N2} f^2_{i,t}} \tag{C.44}$$

Then, a new consumption price index is computed using $f^2_{c,t}$ as weights. The second and further rounds of distribution of consumption demand proceed in a fashion similar to the first one, in each round using the updated market shares and consumption price indices to distribute the remaining household consumption demand among those C-Firms which still have some remaining goods to sell. The only difference between some round $n > 1$ and the first round are that:

- $l_{c,t}$ is left unchanged.
- If $Dem^n_{c,t}$ is smaller than the remaining stock of output of c, $Dem_{c,t}$ is still augmented by $Dem^n_{c,t}$ but if $Dem^n_{c,t}$ exceeds the remaining output stock of c, $Dem^n_{c,t}$ is only augmented by the quantity actually sold by c in round n, to avoid excessive over-production in $t + 1$.

The distribution of consumption demand continues until either households' consumption demand has been fully satisfied or until no C-Firm has any more output left to sell. Following this, the consumption price index is recomputed using actual sales. Any output remaining unsold is scrapped.

C.4.7 Profits and Dividends

Once all C-Firm decisions and market interactions have taken place, gross profits, on which taxes are paid, can be computed: Sales and changes in the nominal value of the capital stock enter the profit calculation with a positive sign; nominal investment, the wage bill, the energy bill and interest on loans enter the profit calculation with a negative sign.

$$\Pi^{gross}_{c,t} = Sales_{c,t} + \Delta K_{c,t} - I_{c,t} - W_{c,t} - En_{c,t} - iL_{c,t} \tag{C.45}$$

Where:

$$\begin{aligned}
Sales_{c,t} &= p_{c,t} Q^s_{c,t} \\
\Delta K_{c,t} &= I_{c,t} - Scrap_{c,t} \\
I_{c,t} &= EI^n_{c,t} + SI^n_{c,t} \\
W_{c,t} &= w_t L_{c,t} \\
En_{c,t} &= p_{e,t} En^d_{c,t} \\
iL_{c,t} &= r^l_{c,t} \mathfrak{l}_{c,t}
\end{aligned} \tag{C.46}$$

- $Q^s_{c,t} \equiv$ quantity of output sold by c in t;
- $\Delta K_{c,t} \equiv$ period-to-period change in the nominal value of c's capital stock; $I_{c,t} \equiv$ nominal value of capital investment; $Scrap_{c,t} \equiv$ nominal value of scrapped capital goods;
- $EI^n_{c,t} \equiv$ Nominal value of expansion investment; $SI^n_{c,t} \equiv$ Nominal value of substitution investment;

- $W_{c,t} \equiv$ wage bill; $w_t \equiv$ nominal wage rate; $L_{c,t} \equiv$ quantity of labour employed by c.
- $En_{c,t} \equiv$ energy bill; $p_{e,t} \equiv$ price of energy; $En^d_{c,t}$ energy demanded by c
- $iL_{c,t} \equiv$ interest payments on debt; $r^l_{c,t} \equiv$ interest rate on loans charged to c; $\mathfrak{l}_{c,t} \equiv$ loan stock of c;

In addition to paying interest on loans, each C-Firm c must also repay a fraction ξ_C of its outstanding stock of loans at the end of every period. Bank loans in the model can hence be interpreted as a type of credit line provided by the banks, with outstanding credit having to either be renewed/rolled over or repaid in full at the beginning of every period t. In addition, banks demand that borrowers reduce any debt taken on/rolled over at the beginning of t by a fraction ξ_C once they have received revenues at the end of t.

If gross profits are positive, firms pay profit taxes, which are charged at a constant and flat rate τ^C:

$$\Pi^{net}_{c,t} = \left(1 - \mathbf{1}^{\left[\Pi^{gross}_{c,t} > 0\right]} \tau^C\right) \Pi^{gross}_{c,t} \tag{C.47}$$

Where $\mathbf{1}^{\left[\Pi^{gross}_{c,t} > 0\right]}$ is an indicator function taking the value 1 if $\Pi^{gross}_{c,t} > 0$ and 0 otherwise.

If profits are positive, firms pay dividends, $Div_{c,t}$ to households:

$$Div_{c,t} = \mathbf{1}^{\left[\Pi^{net}_{c,t} > 0\right]} \delta^C \Pi^{net}_{c,t} \tag{C.48}$$

Where δ^C is the dividend rate, which is assumed to be constant and homogeneous across C-firms.

C.4.8 Failure

C-Firms go bankrupt if they are unable to meet a payment obligation or if their net worth is negative. When this is the case they exit the market and are replaced by new firms (see Section C.5).

Note that since C-Firms scale back their productive activity and investment if they cannot (fully) finance them, C-Firms never fail due to inability to pay for wages or investment. This is because credit demand is computed when the wage rate and the prices charged by suppliers of capital goods are already known. As discussed above, if a C-Firm is so constrained on the credit market that it cannot finance any production, it exits without producing any output and hence does not have any payment obligations towards households, K-Firms, or the energy sector.

Once production and sales of consumption goods have taken place, C-Firms have a number of other payment obligations on which they can potentially default:

1. **Energy payments**: The first claimant in line is the energy sector, which demands payment for the energy input used in production by C-Firms. Since energy demand is computed before

the current price of energy is known, a C-Firm may be unable to (fully) pay for the energy input it used. If this is the case, the C-Firm in question pays as much as it can and then exits.

2. **Principal and interest payments on loans**: Recall that in addition to paying interest on loans, C-Firms must also repay a fraction ξ_C of loans outstanding at the end of period t. If a C-Firm has insufficient liquidity to make both interest and principal payments, it pays as much as it can and then exits

3. **Tax**: If a firm has insufficient liquidity to make tax payments, it pays as much as it can. However, we assume that a C-Firm which cannot meet a tax payment obligation does not exit.

The reasons for exiting given above all arise due to illiquidity. In addition, a C-Firm also exits if, at the end of a period, its net worth is negative, even when it has been able to meet all payment obligations in that period.

Finally, recall that a C-Firm also exits if its market share falls below a threshold $\mathfrak{f}$. This happens even if the firm has been able to meet all payment obligations and if its net worth is positive.

C.5 Firm exit and entry

As described above, both K-Firms and C-Firms may exit the model economy for a variety of reasons such as having zero customers (K-Firms), a very low market share (C-Firms) or being unable to meet a payment obligation (both). In all cases, exiting firms are replaced one for one with new firms of the same type, meaning that the numbers of both K-Firms and C-Firms are constant throughout a simulation. We begin by describing the exit and replacement process for K-Firms and subsequently turn to C-Firms.

C.5.1 Capital good firm replacement

K-Firms hold bank deposits as their only asset and have no liabilities. This also implies that illiquidity and insolvency always coincide in the case of K-Firms.

If a K-Firm k exits, it loses any customers it may still have. However, any capital goods ordered by customers of k in t are still delivered at the beginning of $t+1$. Any deposits which k still holds are transferred to the household sector. Next, a random surviving K-Firm i is drawn. The initial production technique and capital good vintage produced by the new K-Firm j replacing k is copied from the randomly drawn i. Similarly, j's initial selling price is copied from i.

The new K-Firm j receives a transfer of deposits from households in order to provide it with an initial stock of liquidity. This transfer is given by

$$T_{j,t} = \mathfrak{d}_{j,t}\overline{D}_{k,t} \tag{C.49}$$

where $\mathfrak{d}_{j,t}$ is a uniform random variable drawn from the interval $\left(\mathfrak{d}_K^1, \mathfrak{d}_K^2\right)$ and $\overline{D}_{k,t}$ is the average stock of deposits held by surviving K-Firms. The bank serving the new K-Firm j is the same which was serving the exiting firm k.

If households are unable to fully cover the injection of liquidity for entering K-Firms from their accumulated deposits, the remainder is instead covered by the government.

The number of brochures which an entering K-Firm j will send to potential customers in the following period is initialised to $\lfloor \Gamma\mathfrak{n} \rceil$, where $\mathfrak{n}$ is homogeneous across K-Firms. The sales of j, which are needed to determine its initial R&D spending, are initialised to $p_{j,t}\mathfrak{n}$.

C.5.2 Consumption good firm replacement

If, at the time of exit, a C-Firm c's deposits exceed its outstanding loans (this may happen if it exits due to low market share), c's deposits are used in order to pay off the outstanding loans, with the remainder being transferred to households. The link between c and its current capital goods supplier in the C-Firm-K-Firm network is deleted.

If, instead, c's outstanding loans exceed its deposits at the time of exit, the difference between loans and deposits is initially recorded as a loss for the bank serving c. In this case, too, the link between c and its current capital goods supplier in the C-Firm-K-Firm network is severed.

Recall from the above description of C-Firm bankruptcy that C-Firms can never fail due to an inability to pay for investment in capital goods. However, when a C-Firm fails, all capital goods which had been ordered and paid for by that firm in t to be delivered in $t+1$ are scrapped. What happens to any capital goods already held by c is determined by a stylised second hand market for capital goods. The routine of this market begins with the determination of the overall number of machine tools needed by newly entering C-Firms. This is given by

$$mach_t^{entry} = max\left(N2_t^{exit}, ceil\left(f_t^{entry}\frac{Dem_t^{\Sigma}}{u\mathfrak{Q}}\right)\right) \tag{C.50}$$

where

- $N2_t^{exit}$ is the number of C-Firms which exit in t and which hence have to be replaced (this ensures that each newly entering C-Firm will enter with at least one machine).
- Dem_t^{Σ} is the sum of demand for consumption goods experienced by C-Firms in t, i.e. the sum of $Dem_{c,t}$ described above, summed across all C-Firms.
- u is the fixed and exogenous desired capacity utilisation of C-Firms.

- $\mathfrak{Q}$ is the uniform and constant maximum amount of output which can be produced using one machine.

- f_t^{entry} is the overall initial market share of entering C-Firms. If the sum of the market shares of exiting C-Firms, f_t^{exit}, is positive, we set $f_t^{entry} = f_t^{exit}$. If f_t^{exit} is zero, we instead set $f_t^{entry} = N2_t^{exit}\mathfrak{f}^{entry}$ where $\mathfrak{f}^{entry}$ is a parameter with a small positive value.

Next, $mach_t^{entry}$ is compared to $mach_t^{exit}$, the overall number of machines still held by exiting C-Firms. If $mach_t^{entry} > mach_t^{exit}$, the model sets $mach_t^{entry} = mach_t^{exit}$. Having determined the number of machine tools needed/available for newly entering C-Firms, the remaining capital goods of exiting C-Firms are first ordered according to their cost-efficiency (i.e. the unit cost implied by using them in the production of consumption goods). Next, the model iterates over these remaining machines, starting from the most cost-efficient one, until $mach_t^{entry}$ is reached (any remaining machines beyond $mach_t^{entry}$ are scrapped). For each machine m reached by this iteration process, the following operations take place:

1. The nominal value of m is multiplied by $1 - \frac{age_m}{\aleph^K}$, where age_m is the age of m and $\aleph^K$ is the uniform maximum age of machine tools. Machines on the second hand market for capital goods are hence re-valued according to their remaining lifespan.

2. If the exiting C-Firm c which owns m has paid off all outstanding loans using its remaining deposits, m is transferred to the household sector at no cost.

3. If c still has outstanding loans from its bank, the bank takes possession of m in order to subsequently sell m to the household sector. The outstanding loans of c are reduced by the updated nominal value of m.

Following this iteration, all capital goods taken into possession by banks are purchased by the household sector at their new marked-down value. Losses on loans taken by the banks are reduced by the amount they were able to recover through this process. If households are unable to (fully) finance the purchase of second-hand capital goods using accumulated deposits, the remaining cost is covered by the government.

Once the second hand market for capital goods has closed, the initialisation of newly entering C-Firms begins. First, the number of machines which will be assigned to each newly entering C-Firm is determined. Initially, each entering firm is assigned one machine. Any remaining machines from the pool of second-hand capital goods are then assigned randomly, with each entering C-Firm receiving $floor\left(\left(mach_t^{entry} - N2_t^{exit}\right)\frac{\varepsilon_{c,t}^{entry}}{\sum_{i=1}^{N2}\varepsilon_{i,t}^{entry}}\right)$ where $\varepsilon_{i,t}^{entry}$ is given by a draw from a uniform distribution on the interval $[0, 1]$ for entering C-Firms and set to 0 for surviving ones. Any second-hand machines still remaining after this process are assigned one by one to randomly drawn entering firms. Having thus determined the number of machines which each entering C-Firm will receive, the actual machines assigned to each individual entering C-Firm are drawn randomly from the pool of second hand capital goods available and transferred to the balance sheets of entering firms.

Next, each entering C-Firm receives a transfer of bank deposits from the household sector. Similarly to the case of K-Firms, the transfer received by an entering C-Firm i is given by

$$T_{i,t} = \mathfrak{d}_{i,t}\overline{D}_{c,t} \tag{C.51}$$

where $\mathfrak{d}_{i,t}$ is a uniform random variable drawn from the interval $\left(\mathfrak{d}^1_C, \mathfrak{d}^2_C\right)$ and $\overline{D}_{c,t}$ is the average stock of deposits held by surviving C-Firms. As in the case of K-Firms, if households are unable to (fully) finance this transfer, it is covered by the government. The bank serving the new C-Firm i is the same which was serving the exiting firm c which i replaces. In addition, each entering C-Firm is assigned a randomly drawn initial supplier of capital goods.

Based on the initial stock of capital goods received through the second hand market, an entering C-Firm i computes its unit cost. Its mark-up is initialised to an exogenous value μ^{entry}. It then sets its initial price using this unit cost and mark-up

$$\begin{aligned} \mu_{i,t} &= \mu^{entry} \\ p_{i,t} &= \left(1 + \mu_{i,t}\right) uc_{i,t} \end{aligned} \tag{C.52}$$

Recall that f^{entry}_t is the overall market share which will be assigned to entering C-Firms. To allocate this share among individual entering firms the model uses a simplified form of the quasi-replicator dynamics described in Section C.4. In particular, the competitiveness of an entering C-Firm i is given by

$$E^{entry}_{i,t} = -\frac{p_{i,t}}{\hat{p}^{entry}_t} \tag{C.53}$$

i.e., it is a function of its price relative to the average price across entering C-Firms, $\hat{p}^{entry}_t$. The share of f^{entry}_t which i will receive is computed as

$$share^{entry}_{i,t} = \frac{1}{N2^{exit}_t}\left(\frac{2\omega_3}{1 + e^{\left(-\chi\frac{E^{entry}_{i,t} - \overline{E}^{entry}_t}{\overline{E}^{entry}_t}\right)}} + \left(1 - \omega_3\right)\right) \tag{C.54}$$

which is then normalised. The initial consumption good market share of the entering C-Firm i is given by

$$\tilde{f}_{i,t} = f^{entry}_t share^{entry}_{i,t} \tag{C.55}$$

$\tilde{f}_{i,t}$ is then used to initialise the entering C-Firm's expected demand, ability to satisfy demand, sales and net revenue:

$$
\begin{aligned}
Dem_{i,t} &= min\big(\mathfrak{K}_{i,t}, \tilde{f}_{i,t} Dem_t^{\Sigma}\big) \\
Dem_{i,t}^{e} &= Dem_{i,t} \\
l_{i,t} &= 1 + \tilde{f}_{i,t} Dem_t^{\Sigma} - Dem_{i,t} \\
Sales_{i,t} &= p_{i,t} Dem_{i,t} \\
NR_{i,t} &= Sales_{i,t} - uc_{i,t} Dem_{i,t}
\end{aligned}
\tag{C.56}
$$

where $\mathfrak{K}_{i,t}$ is the productive capacity of i based on the capital goods it received from the second-hand market and Dem_t^{Σ} is the sum of consumption demand received by all C-Firms in t. Once all entering C-Firms have been assigned a market share, the market shares of all C-Firms (i.e. both entering and surviving ones) are normalised to ensure that they sum to one.

C.6 Banks

The banking sector consists of NB individual banks. We use the index b, where $b = 1, ..., NB$ to denote individual banks. All banks are functionally identical, but banks differ in the number of individual firm customers that are assigned to them at the beginning of a simulation. Since each bank serves a different set of customers, both the size and composition of individual banks' balance sheets are heterogeneous.

C.6.1 Distribution of customers

At the beginning of a simulation, individual K-Firms and C-Firms are allocated to the banks as customers. The initial distribution of the number of C-Firm customers per bank is assumed to follow a truncated Pareto distribution with lower bound $\mathfrak{p}_1^C$, upper bound $\mathfrak{p}_2^C$, and shape parameter $\mathfrak{p}$. Similarly, the initial distribution of the number of K-Firm customers per bank is assumed to follow a truncated Pareto distribution with lower bound $\mathfrak{p}_1^K$, upper bound $\mathfrak{p}_2^K$, and shape parameter $\mathfrak{p}$. Banks' balance sheets are initialised using this distribution of firm customers. Aggregate stocks such as household deposits are initially distributed in line with the share of firm customers of each bank (i.e. each bank receives a share $\frac{clients_b}{N1+N2}$, where $clients_b$ is the number of K-Firm and C-Firm customers of b). The distribution of firm clients subsequently remains fixed. If a firm exits the model, the new firm replacing it becomes a customer of the same bank.

C.6.2 Deposits

The main liability of the banking sector are unremunerated deposits, which are held by firms, households and the energy sector. Changes in the deposits of a firm are reflected in a corresponding change in the deposits on the liability side of the balance sheet of that firm's bank. Changes in aggregate deposit stocks (households and energy sector) are distributed among individual banks using their previous market share in the respective deposit market. For instance, if a change occurs in the stock of deposits held by households (such as when households receive wage payments), the stock of household deposits on the balance sheet of bank b changes by $\Delta D_h \frac{D_{h,b}}{\sum_{b=1}^{NB} D_{h,b}}$.[16]

C.6.3 Loans

On the asset side, the main activity of banks consists in lending to the C-Firm sector. C-Firms' loan demand was described in Section C.4.4. On the supply side, every bank sets a maximum overall amount of loans it is prepared to hold on its balance sheet in t, which is given defined by a fixed capital adequacy ratio target:

$$\mathfrak{C}^s_{b,t} = \frac{NW_{b,t}}{CAR^* RW_l} \tag{C.57}$$

where $NW_{b,t}$ is the net worth of bank b, CAR^* is a fixed target capital adequacy ratio, and RW_l is a fixed and homogeneous risk weight on bank loans. Note that this formulation implies that the risk weight on all other bank assets is zero.

Once banks determine the maximum amount of credit they are willing to extend, they decide on credit applicants. The first choice to be made regards the interest rate to be charged. For this purpose, each bank ranks all of its C-Firm customers in ascending order according to their debt service-to-revenue ratio. C-Firms with lower ratios are considered more credit-worthy than firms with higher ratios. The more credit-worthy a C-Firm is perceived to be, the lower the loan interest rate that its bank will charge:

$$r^l_{b,c,t} = r^l_{b,t} + \big(rank_{c,t} - 1\big)\mathfrak{M} \tag{C.58}$$

Where:

- $r^l_{b,c,t} \equiv$ the interest rate on loans charged by bank b, to firm c, at time t. Note that since the credit network is static, i.e. firms do not change banks we usually omit the b subscript.
- $r^l_{b,t} \equiv$ bank b's baseline loan rate, defined as:

$$r^l_{b,t} = r^l_{CB,t-1} + \mu^B \tag{C.59}$$

[16] If the stock of aggregate household or energy sector deposits should become zero, the market shares are re-initialised using each bank's number of firm customers.

Where $r^l_{CB,t-1}$ is the lending rate set by the central bank and μ^B is a constant and homogeneous mark-up, meaning that $r^l_{b,t}$ is identical across banks

- $\mathfrak{M} \equiv$ a parameter
- $rank_{c,t} \equiv$ the quartile of the distribution of debt service-to-revenue ratios among b's customers to which c belongs

In addition to interest rate discrimination, bank b will also engage in credit rationing whenever the total demand for credit exceeds the maximum it is willing to extend, $\mathfrak{C}^s_{b,t}$. For this purpose, banks again use the debt service-to-revenue ranking to determine the order in which credit demand is satisfied. First, the most credit-worthy customer, c^*, is served. The amount of credit extended to c^* is the minimum between c^*'s credit demand and b's maximum credit supply, i.e. $max\big(\mathfrak{C}^s_{b,t}, \mathfrak{l}^d_{c^*,t}\big)$. If $\mathfrak{C}^s_{b,t} \geq \mathfrak{l}^d_{c^*,t}$, c^* is served in full, b reduces the remaining amount of credit it is willing to extend by the amount given to c^*, and moves to the next customer in the ranking. If $\mathfrak{C}^s_{b,t} < \mathfrak{l}^d_{c^*,t}$, c^*'s credit demand is reduced by cutting investment expenditure and possibly planned production, until the credit required by c^* can be provided by b (see Section C.4.4). All subsequent customers of b are then denied credit. The procedure continues up to the point at which either all applicants have been given credit or b's credit supply is exhausted.

C.6.4 Demand for government bonds

Bank b's demand for additional government bond holdings is set as:

$$\Delta^d_{GB_{b,t}} = max\left(0, \mathfrak{G} \sum_{c \in \Phi_{b,c}} \mathfrak{l}_{c,t} - GB_{b,t-1}\right) \tag{C.60}$$

Where $\Delta^d_{GB_{b,t}}$ is the desired change in the stock of bonds held by b and $\sum_{c \in \Phi_{b,c}} \mathfrak{l}_{c,t}$ is the loan stock held by b, with $\Phi_{b,c}$ being the set of C-Firms who are customers of b. $GB_{b,t-1}$ is the stock of government bonds accumulated up to the previous period and $\mathfrak{G}$ is an exogenous parameter, which can be interpreted as the bank's desired government bond to loans ratio. Note that this formulation implies that banks cannot sell government bonds. The supply side of the government bond market is described in Section C.7.

C.6.5 Profits and dividends

Once all bank decisions and market interactions have taken place, gross profits, on which taxes are paid, can be computed: interest payments on loans and government bonds enter the profit calculation with a positive sign; interest payments on central bank advances, as well as losses stemming from bad debt (net of recovered collateral) enter the profit calculation with a negative sign:

$$\Pi_{b,t}^{gross} = \sum_{c \in \Phi_{b,c}} r_{b,c,t}\mathfrak{l}_{c,t} + r_{GB,t-1}GB_{b,t-1} - r_{CB,t-1}^{l}A_{b,t-1} - (BD_{b,t} - CR_{b,t}) \tag{C.61}$$

Where:

- $\Phi_{b,c} \equiv$ subset of consumption firm clients of b; $\mathfrak{r}_{b,c,t} \equiv$ loan interest rate charged by bank b to firm c; $\mathfrak{l}_{c,t} \equiv$ outstanding loans to c.[17]
- $r_{GB,t-1} \equiv$ interest rate on government bonds; $GB_{b,t-1} \equiv$ public debt held by bank b.
- $r_{CB,t-1}^{l} \equiv$ central bank lending rate; $A_{b,t-1} \equiv$ stock of central bank advances to b.
- $BD_{b,t} \equiv$ value of defaulted debt; $CR_{b,t} \equiv$ recovered collateral from failed firms (see Section C.5).

If profits are positive, banks pay a fraction τ^B of them in taxes, making net profits:

$$\Pi_{b,t}^{net} = \left(1 - \mathbf{1}^{[\Pi_{b,t}^{gross}>0]}\tau^B\right)\Pi_{b,t}^{gross} \tag{C.62}$$

Where $\mathbf{1}^{[\Pi_{b,t}^{gross}>0]}$ is an indicator variable taking the value 1 if $\Pi_{b,t}^{gross} > 0$ and 0 otherwise.
In addition, if profits are positive, dividends are paid at an exogenous and homogeneous rate:

$$Div_{b,t} = \mathbf{1}^{[\Pi_{b,t}^{net}>0]}\delta^B\Pi_{b,t}^{net} \tag{C.63}$$

C.6.6 Net worth and bankruptcy

Banks' net worth is updated in each period according to:

$$NW_{b,t} = NW_{b,t-1} + \Pi_{b,t}^{gross} - Div_{b,t} - Tax_{b,t} \tag{C.64}$$

Where $Tax_{b,t}$ are taxes paid by bank b (see also Section C.7).

A bank fails if $NW_{b,t} < 0$. In the model version used in the present paper, it is assumed that failing banks are always bailed out by the government. When a bank b fails, the government determines a specific bailout which re-sets its net worth to:

$$NW_{b,t} = Bail_{b,t} \tag{C.65}$$

[17] Note that for exiting C-Firms $\mathfrak{l}_{c,t}$ has already been set to 0.

$Bail_{b,t}$, in turn, is determined as:

$$Bail_{b,t} = max\left(-NW_{b,t} + CAR^{*} RW_{l} \sum_{c \in \Phi_{b,c}} \mathfrak{l}_{c,t}, -NW_{b,t} + mb_{b,t} NW^{*}_{b,t} \right) \tag{C.66}$$

Where $NW_{b,t}$ is to be understood as the (negative) net worth of b *prior* to being bailed out and $\sum_{c \in \Phi_{b,c}} \mathfrak{l}_{c,t}$ is b's existing stock of loans. $mb_{b,t}$ is an individual bailout multiplier, given by a random draw from a uniform distribution on the support $\left(\mathfrak{d}^{1}_{B}, \mathfrak{d}^{2}_{B}\right)$. Finally, $NW^{*}_{b,t}$ is calculated as follows: Let v denote the bank among the set of surviving banks which has the highest net worth *per customer* in t (i.e. the bank for which $\frac{NW_{v,t}}{clients_{v}}$ takes the highest value). $NW^{*}_{b,t}$ is determined by taking this maximum net worth per customer and multiplying it by the number of firm customers served by the failing bank b.[18]

C.7 Government

The government collects taxes on firm and banking sector profits as well as on emissions from the energy sector.

Taxes on C-Firms are given by

$$Tax^{C}_{t} = \sum_{c=1}^{N2} \tau^{C} \mathbf{1}^{\mathbf{\Pi}}_{\mathbf{c}} \Pi_{c,t} \tag{C.67}$$

summing across all $N2$ C-Firms. $\Pi_{c,t}$ is the profit of C-Firm c in period t. $\mathbf{1}^{\mathbf{\Pi}}_{\mathbf{c}}$ is an indicator function taking the value 1 if $\Pi_{c,t} > 0$ and 0 otherwise. Similarly, taxes paid by K-Firms are given by

$$Tax^{K}_{t} = \sum_{k=1}^{N1} \tau^{K} \mathbf{1}^{\mathbf{\Pi}}_{\mathbf{k}} \Pi_{k,t} \tag{C.68}$$

Finally, banks pay taxes on positive profits, while the energy sector is assumed to pay taxes only on emissions.

$$Tax^{B}_{t} = \sum_{b=1}^{NB} \tau^{B} \mathbf{1}^{\mathbf{\Pi}}_{\mathbf{b}} \Pi_{b,t} \tag{C.69}$$

$$Tax^{E}_{t} = \tau^{Em,E}_{t} Em_{e,t} \tag{C.70}$$

Total tax revenue is then given by the sum of the tax revenue received from the different sectors:

[18] If all banks fail in t, $NW^{*}_{b,t}$ is replaced with $NW_{b,t-1}$ in Equation (C.66). Note that $NW_{b,t-1}$ is always positive since it is calculated after bailouts occur in $t-1$.

$$Tax_t = Tax_t^C + Tax_t^K + Tax_t^B + Tax_t^E \tag{C.71}$$

In addition, any profits made by the central bank, $\Pi_{cb,t}$ (described below) are paid to the government as a transfer $T_{cb,t}$. Importantly, this also applies if the central bank makes a loss, i.e. central bank losses are compensated by the government.

In the present paper, the emissions tax rate on the energy sector, $\tau_t^{Em,E}$, is set to grow with nominal GDP from an exogenously set initial value:

$$\tau_t^{Em,E} = \tau_0^{Em} \frac{GDP_{t-1}^n}{GDP_1^n} \tag{C.72}$$

where GDP_1^n is nominal GDP in the first simulation period. The emission tax is activated in the first post-transient period in which the climate module is called and subsequently updated every four periods (i.e. every year).

The main expenditure item of the government are unemployment benefits paid to households. As explained above, in any given period t, households will supply any amount of labour demanded at the current wage rate up to a maximum LS_t, which represents the current labour force. With L_t being the amount of labour actually employed in t, unemployment is given by $LS_t - L_t$. The unemployment benefit is given by a fraction ζ of the current nominal wage, making total unemployment benefit payments

$$UB_t = \zeta w_t \big(LS_t - L_t\big) \tag{C.73}$$

In addition, the government may have expenditures to finance the entry of new firms and for the bailout of failing banks.

Finally, the government makes interest payments on the stock of outstanding government bonds, GB_{t-1}, given by

$$iGB_t = r_{GB,t-1} GB_{t-1} \tag{C.74}$$

where $r_{GB,t-1}$ is the nominal interest rate on government bonds.

The overall budget balance of the government is hence given by

$$Sav_{g,t} = Tax_t + T_{cb,t} - UB_t - iGB_t - T_{g,t} - Bail_t \tag{C.75}$$

In addition to expenditures, the government must also roll over outstanding debt; in the present paper it is assumed that the entire stock of outstanding bonds must be rolled over in every period. The ‘public sector borrowing requirement’ hence becomes:

$$PSBR_t = UB_t + iGB_t + T_{g,t} + Bail_t + GB_{t-1} - Tax_t - T_{cb,t} \tag{C.76}$$

New government bonds are in the first instance offered to banks, which demand bonds according to the rule set out in Section C.6. Any new bonds which are not acquired by banks are assumed to be purchased by the central bank. The current interest rate on government bonds, $r_{GB,t}$, is assumed to be equal to the central bank's lending rate (the determination of which is described below) and applies to all outstanding government debt.

C.8 Central bank

The central bank in the model is tasked with maintaining the payments system and setting the base interest rate. In setting its lending rate, the central bank follows a Taylor-type rule given by

$$r^l_{CB,t} = max\Big(\underline{r}, \iota_1 r^l_{CB,t-1} + \big(1-\iota_1\big)\big(r + \iota_2\big(\pi^a_t - \pi^*\big) + \iota_3(U^* - U_t)\big)\Big) \tag{C.77}$$

where ι_1 is an interest rate smoothing parameter, r is a fixed intercept, π^a_t is the current year-on-year inflation rate with π^* being the year-on-year inflation target, U_t being the current unemployment rate and U^* the central bank's target unemployment rate. $\underline{r}$ is a fixed lower bound close to 0. Since the model is calibrated to be simulated at quarterly frequency, this annual lending rate is subsequently converted to a quarterly one. The central bank deposit rate is set to 0.

The central bank maintains the payments system in the model by supplying reserves required to settle interbank transactions. For simplicity, the model currently does not include an interbank market. Instead, all transactions implying flows of reserves from one bank to another are recorded over a period. At the end of every period, a net in- or outflow of reserves is calculated for each individual bank. If a bank has experienced a net outflow of reserves, it first makes use of any existing reserve balances to cover this outflow. If the stock of reserves it currently holds is insufficient, the central bank provides advances on demand at the current central bank lending rate. The bank then uses these reserves borrowed from the central bank to cover its net outflow. Conversely, the reserve balance of every bank experiencing a net inflow of reserves is augmented by the size of that net position. If a bank experiencing a net inflow of reserves has outstanding advances from the central bank, it uses the inflow of reserves to repay as much of these advances as possible and accumulates any remaining reserves on its balance sheet.

In order to enable the stylised modeling of an 'external' fossil fuel supplier as described below, the fossil fuel sector is not directly linked to the commercial banking system but instead holds a reserve account with the central bank. When the energy sector makes a payment to the fossil fuel sector, this hence implies a net outflow of reserves for the commercial banking system as a whole, which is accumulated in the reserve account of the fossil fuel sector. In contrast to commercial banks, the fossil fuel sector is not able to borrow reserves from the central bank.

C.9 Energy Sector

The energy sector consists of a single representative agent which sells energy as an input to K-Firms and C-Firms. Energy is produced using both ‘green’ and ‘brown’ technologies, possibly with multiple plants of each technology and of different vintages operational at any given time.

C.9.1 Capacity expansion

The total amount of energy produced is determined by the overall demand for energy from C-Firms and K-Firms. Based on the amount of consumption goods and capital goods produced in t and the energy efficiency of the capital vintages and production techniques utilised to do so, a total demand for energy, En_t^d is calculated.

The existing productive capacity of the energy sector is given by $\mathfrak{K}_{e,t-1}$, expressed in units of energy producible. This productive capacity can in turn be divided into a capacity for producing ‘brown/dirty’ $\left(\mathfrak{K}_{t-1}^{de}\right)$ and ‘green/clean’ $\left(\mathfrak{K}_{t-1}^{ge}\right)$ energy. At present, the modelling of green and brown energy technologies is strongly stylised and simplified; in particular, green and brown energy plants differ in the following respects:

- Green energy production does not give rise to greenhouse gas emissions, while the emission intensity of brown energy production is positive.
- The production of energy from existing green energy plants is assumed to be costless, whereas the production of energy from brown energy plants requires a costly fossil fuel input.
- The expansion of productive capacity is assumed to be costless for brown energy plants, while additions to the productive capacity of green energy have a positive cost.

if $En_t^d > \left(\mathfrak{K}_{t-1}^{de} + \mathfrak{K}_{t-1}^{ge}\right)$, the energy sector must expand its productive capacity to meet the model’s current demand for energy. In order to avoid situations in which current production of output is constrained by the availability of energy, it is assumed that the energy sector can expand its capacity instantaneously. In the present paper, it is assumed that the shares of green and brown capacity in total capacity are exogenously given and constant, and expansion investment in both technologies is made according to these shares.

For every vintage κ^{de} of brown energy technologies, the per-unit production cost of energy is given by:

$$c_{\kappa^{de},t} = \frac{p_{f,t-1}}{TE_{\kappa^{de}}} + \tau_t^{Em,E} EF_{\kappa^{de}} \tag{C.78}$$

where $p_{f,t-1}$ is the price of the fossil fuel input to be paid in the current period, $TE_{\kappa^{de}}$ denotes the thermal efficiency of vintage κ^{de}, $\tau_t^{Em,E}$ is the current value of the tax on emissions applied to the energy sector, and $EF_{\kappa^{de}}$ is the emission intensity of vintage κ^{de}.

As indicated above, the production of green energy is assumed to be costless. However, the expansion of green energy production capacity (which is assumed costless for brown energy) carries a positive cost. For every vintage κ^{ge}, the expansion/investment cost per unit of productive capacity is given by $c_{\kappa^{ge},t}$. Since in the absence of shocks, both the carbon tax and the fossil fuel price grow over time (the former with nominal GDP and the latter with the nominal wage, see below), it is assumed that the expansion cost for each green energy technology vintage κ^{ge} grows with a weighted average of past changes in the nominal wage to keep it in line with the rest of the model.

To determine the green and brown technologies to invest in when expanding capacity, the energy sector determines the minimum $c_{\kappa^{ge},t}$ and $c_{\kappa^{de},t}$ among all vintages κ^{de} and κ^{ge}. While expansion of brown energy capacity is costless, green capacity expansion incurs the per-unit cost $c^{min}_{\kappa^{ge},t}$, making the total cost of green energy investment $c^{min}_{\kappa^{ge},t}EI^{ge}_t$, where EI^{ge}_t is the additional capacity for green energy production installed in t. It is assumed that this cost is staggered over the payback period b^e of the investment. This means that if the energy sector invests in green energy capacity in t, it will incur a cost $IC_{e,t} = \frac{c^{min}_{\kappa^{ge},t}EI^{ge}_t}{b^e}$ in t as well as in the following $b^e - 1$ periods. This cost is transformed into an associated demand for labour by dividing it by the current nominal wage rate, $\frac{IC^e_t}{w_t}$.

For accounting purposes, the productive capacity of the energy sector is valued at installation cost. This implies that the nominal value of brown capacity is zero, while the nominal value of a unit of existing green capacity is given by the construction cost incurred. All energy production plants are assumed to have a fixed lifetime of $\aleph^E$ periods after which they are written off and scrapped.

C.9.2 Production and sales

Having expanded capacity if necessary, the energy sector satisfies the demand for energy by activating plants in the order of their cost-effectiveness. Since the production cost for green energy is assumed to be zero, green plants are always activated first. If the existing green capacity is insufficient to satisfy all energy demand, brown plants are activated starting from the one with the lowest unit cost of production.

The uniform price of energy to be paid by all firms is then given by

$$p_{e,t} = \mu_{e,t} + mc_{e,t} \tag{C.79}$$

$\mu_{e,t}$ is a mark-up, while $mc_{e,t}$ denotes the marginal cost of energy production, i.e. the unit cost of production of the last (and hence least cost-effective) plant activated to satisfy energy demand in t. If no brown energy is produced in t, $mc_{e,t} = 0$. The mark-up $\mu_{e,t}$ is assumed to change over time according to:

$$\mu_{e,t} = \mu_{e,t-1} * \overline{\Delta}_{w,t} \tag{C.80}$$

where $\overline{\Delta_{w,t}}$ is a weighted average of current and past changes in the nominal wage rate:

$$\overline{\Delta}_{w,t} = \eta\overline{\Delta}_{w,t-1} + (1-\eta)\frac{w_t}{w_{t-1}} \tag{C.81}$$

This assumption is made to ensure that in the absence of shocks, the price of energy grows roughly in line with the nominal size of the overall economy. This is important in particular since, as discussed below, the baseline calibration used in this paper leads to a roughly constant real energy use.

If brown energy is produced in t, the energy sector also calculates the fossil fuel input required by the activated vintages, as well as the emissions resulting from production. Having received revenue from the sale of energy, the energy sector makes a payment for the fuel inputs to the fossil fuel sector (described below) and pays the emission tax.

C.9.3 R&D

It is assumed that the energy sector wishes to devote a share $\mathfrak{o}^e$ of its revenue to R&D activities. R&D expenditure is given by

$$RD_{e,t} = \mathfrak{o}^e p_{e,t} En^d_t \tag{C.82}$$

if $\mathfrak{o}^e p_{e,t} En^d_t < p_{e,t} En^d_t - IC_{e,t} - PC_{e,t}$, and

$$RD_{e,t} = max\left(0, \mathfrak{o}^e p_{e,t}\left(En^d_t - IC_{e,t} - PC_{e,t}\right)\right) \tag{C.83}$$

otherwise, where $IC_{e,t}$ is the cost paid in t for capacity expansion as described above and $PC_{e,t}$ denotes the total cost of energy production, including costs for fossil fuel inputs and the emissions tax. The division of R&D expenditure between green and brown technology, $RD_{ge,t}$ and $RD_{de,t}$ is endogenous, with the share devoted to brown technologies corresponding to the share of brown energy in total energy produced in t

As in the case of K-Firms, R&D is carried out using labour as an input:

$$\begin{aligned} L^{rd}_{de,t} &= \frac{RD_{de,t}}{w_t} \\ L^{rd}_{ge,t} &= \frac{RD_{ge,t}}{w_t} \end{aligned} \tag{C.84}$$

Since the energy sector only contains a single representative agent, R&D activities are fully devoted to innovation (recall that, by contrast, K-Firms may also imitate the technology of a competitor). The probability of an innovation taking place in green/brown energy technology is a function of the amount of labour devoted to R&D to each technology:

$$\begin{aligned} P(Innovation\ Brown) &= 1 - exp\big(-\mathfrak{b}_1^E L_{de,t}^{rd}\big) \\ P(Innovation\ Green) &= 1 - exp\big(-\mathfrak{b}_1^E L_{ge,t}^{rd}\big) \end{aligned} \tag{C.85}$$

The determination of the characteristics of the innovated technologies then proceeds in the same fashion as in the case of K-Firms. If innovation in brown technology takes place, a random draw is made from a beta distribution with shape parameters $\mathfrak{b}_2^E$ and $\mathfrak{b}_3^E$ over the support $\big(\mathfrak{b}_4^E, \mathfrak{b}_5^E\big)$. The random number $\mathfrak{I}_{de,t}$ thus drawn is used to determine the thermal efficiency and emission intensity of the new technology based on the characteristics of the current most efficient technology:

$$\begin{aligned} TE_{inn} &= TE_{\kappa^{de}}\big(1 + \mathfrak{I}_{de,t}\big) \\ EF_{inn} &= EF_{\kappa^{de}}\big(1 - \mathfrak{I}_{de,t}\big) \end{aligned} \tag{C.86}$$

where $TE_{\kappa^{de}}$ is the thermal efficiency of the current vintage of brown energy technology, and $EF_{\kappa^{de}}$ is the emission intensity of that vintage. The innovated brown technology is adopted if the unit cost of producing energy using this technology (taking into account both fuel cost and emission tax payments) is lower than that of the current vintage κ^{de}. Otherwise, the current vintage remains unchanged.

If innovation in green technology takes place, a draw is made from the same beta distribution described above. The new random number $\mathfrak{I}_{ge,t}$ thus drawn is used to determine the per-unit expansion investment cost of the innovated green technology on the basis of the characteristics of the current vintage, κ^{ge}

$$c_{ge}^{inn} = c_{\kappa^{ge}}\big(1 - \mathfrak{I}_{ge,t}\big) \tag{C.87}$$

As in the case of brown technology, the innovation is only adopted if the resulting expansion investment cost is lower than that of the current vintage.

C.9.4 Profit and dividends

Having determined its labour demand for R&D activities as well as expansion investment, the energy sector hires workers and pays the corresponding wages to the household sector. Similarly to the case of labour employed for R&D purposes in the K-Firm sector, we assume that the energy sector is never rationed on the labour market when seeking to hire workers.

The energy sector then calculates its current profit as:

$$\Pi_{e,t}^{gross} = Sales_{e,t} - W_{e,t} + \big(K_{e,t} - K_{e,t-1}\big) - CTAX_{e,t} - FF_t \tag{C.88}$$

where:

$$\begin{aligned} Sales_{e,t} &= p_{e,t} En_t \\ W_{e,t} &= w_t L_{e,t} \\ CTAX_{e,t} &= \tau_t^{Em,E} Em_{e,t} \\ FF_t &= p_{f,t} ff_t^d \end{aligned} \tag{C.89}$$

- $Sales_{e,t} \equiv$ nominal sales; $p_{e,t} \equiv$ price; $En_t \equiv$ quantity of energy sold;
- $W_{e,t} \equiv$ wage bill; $w_t \equiv$ nominal wage; $L_{e,t} \equiv$ number of employed workers (for R&D and expansion investment);
- $K_{e,t} - K_{e,t-1} \equiv$ change in the nominal value of the energy sector's capital stock;
- $CTAX_{e,t} \equiv$ emission tax paid; $\tau^{Em,E} \equiv$ tax rate per unit of emission charged to the energy sector; $Em_{e,t} \equiv$ emissions;
- $FF_t \equiv$ cost of fossil fuel input; $p_{f,t} \equiv$ price of fossil fuel; $ff_t^d \equiv$ quantity of fossil fuel demanded;

If $\Pi_{e,t}^{gross}$ is positive, the energy sector pays a constant share δ^E of that profit as dividend to the household sector. As in the case of firms, all retained earnings of the energy sector are held in the form of bank deposits, $D_{e,t}$. In order to distribute (changes in) energy sector deposits among individual banks, the same rule as that applied for households is used (see Section C.6).

C.10 Climate

The climate module runs at annual frequency, such that it is called every four periods. t_0^{clim}, the first period in which the climate module is called, is set to be equal to the first post-transient period of the economic component of the model. Since the calibration depicted in the present paper is intended to depict the EU27 region, emissions are partly exogenous. Exogenous emissions are assumed to grow at a fixed rate g_{Em}. Endogenous emissions are the sum of current emissions from the capital and consumption good sectors and the energy sector.

The climate module similarly receives transformed exogenous and endogenous emissions as an input. It uses them to update the atmospheric carbon content and calculate a global temperature anomaly. It depicts a carbon cycle, in which the atmospheric carbon content (measured in GtC) depends on anthropogenic emissions as well as on carbon exchange between the atmosphere, the oceans and biomass. A global temperature anomaly results from radiative forcing and heat flux between ocean layers. While the climate module is active in the simulations shown in the present paper, climate change impacts are deactivated such that the resulting temperature anomaly does not have any effect on other model variables. More broadly, the paper does not aim to analyse long-run emission and temperature trajectories. The interested reader is referred to Reissl et al. (2024) for a full description of the climate module. The latter document also describes how emissions are transformed prior to being passed to the climate module and contains a broader description of the calculation of aggregate model variables as well as the stock-flow consistency checks which are carried out in every simulation period.

Appendix D Parameters and initial values

Table D1 provides a full list of all economic model parameters with descriptions. It also gives the values used for the simulations shown in this paper. Table D2 contains a list of all initial values needed to simulate the model.

Table D1: Economic model parameters

Symbol	**Description**	**Value**
$N1$	Number of K-Firms	20
$N2$	Number of C-Firms	200
NB	Number of banks	10
g_L	Growth rate of labour force	-1.15e-5
ζ	Unemployment benefit ratio	0.4
α_1	Propensity to consume out of wage & benefit income	0.965
α_2	Propensity to consume out of profit income	0.3
α_3	Propensity to consume out of wealth	0.1
$\overline{\mathfrak{w}}$	Maximum per-period % change in the wage rate	0.025
ψ_1	Sensitivity of nominal wage to inflation gap	0.113
ψ_2	Sensitivity of wage to productivity	1
ψ_3	Sensitivity of nominal wage to unemployment	0.444
η	Parameter used for calculating weighted averages	0.921
$\aleph^K$	Maximum lifespan of machine tools	19
μ^K	K-Firm mark-up	0.1
Γ	# brochures sent by K-Firms (fraction of current customers)	0.194
$\mathfrak{o}$	Share of K-Firm revenue dedicated to R&D	0.055
$\mathfrak{r}^K$	Share of K-Firm R&D dedicated to innovation	0.5

Table D1 – continued from previous page

Symbol	Description	Value
$\mathfrak{b}^K_1$	Parameter governing K-Firm probability of innovating	0.05
$\mathfrak{b}^K_2$	Parameter governing K-Firm probability of imitating	0.05
$\mathfrak{b}^K_3$	Shape parameter of beta distribution for capital vintage labour productivity innovation	1.5
$\mathfrak{b}^K_4$	Shape parameter of beta distribution for capital vintage labour productivity innovation	3
$\mathfrak{b}^K_5$	Lower bound for random capital vintage labour productivity innovation	-0.02
$\mathfrak{b}^K_6$	Upper bound for random capital vintage labour productivity innovation	0.025
$\mathfrak{b}^K_7$	Shape parameter of beta distribution for capital vintage energy efficiency innovation	1.5
$\mathfrak{b}^K_8$	Shape parameter of beta distribution for capital vintage energy efficiency innovation	3
$\mathfrak{b}^K_9$	Lower bound for random capital vintage energy efficiency innovation	-0.01
$\mathfrak{b}^K_{10}$	Upper bound for random capital vintage energy efficiency innovation	0.04225
$\mathfrak{b}^K_{11}$	Shape parameter of beta distribution for capital vintage environmental friendliness innovation	1.5
$\mathfrak{b}^K_{12}$	Shape parameter of beta distribution for capital vintage environmental friendliness innovation	3
$\mathfrak{b}^K_{13}$	Lower bound for random capital vintage environmental friendliness innovation	-0.01
$\mathfrak{b}^K_{14}$	Upper bound for random capital vintage environmental friendliness innovation	0.0225
$\mathfrak{b}^K_{15}$	Shape parameter of beta distribution for labour productivity of K-Firm production technique	1.5
$\mathfrak{b}^K_{16}$	Shape parameter of beta distribution for labour productivity of K-Firm production technique	3
$\mathfrak{b}^K_{17}$	Lower bound for random K-Firm production technique labour productivity innovation	-0.03
$\mathfrak{b}^K_{18}$	Upper bound for random K-Firm production technique labour productivity innovation	0.0535
$\mathfrak{b}^K_{19}$	Shape parameter of beta distribution for energy efficiency of K-Firm production technique	1.5
$\mathfrak{b}^K_{20}$	Shape parameter of beta distribution for energy efficiency of K-Firm production technique	3
$\mathfrak{b}^K_{21}$	Lower bound for random K-Firm production technique energy efficiency innovation	-0.01
$\mathfrak{b}^K_{22}$	Upper bound for random K-Firm production technique energy efficiency innovation	0.0425
$\mathfrak{b}^K_{23}$	Shape parameter of beta distribution for environmental friendliness of K-Firm production technique	1.5
$\mathfrak{b}^K_{24}$	Shape parameter of beta distribution for environmental friendliness of K-Firm production technique	3
$\mathfrak{b}^K_{25}$	Lower bound for random K-Firm production technique environmental friendliness innovation	-0.005

Table D1 – continued from previous page

Symbol	Description	Value
$\mathfrak{b}_{26}^K$	Upper bound for random K-Firm production technique environmental friendliness innovation	0.001
b	Payback parameter	160
τ^K	Tax rate on K-Firm profit	0.1
δ^K	K-Firm dividend payout rate	0.75
σ	C-Firm adaptive demand expectations parameter	0.278
$\mathfrak{Q}$	Maximum output producible with one unit of capital good	40
u	C-Firms' desired capacity utilization	0.8
λ	C-Firm maximum capacity growth	0.25
Δ^μ	C-Firm mark-up adjustment coefficient	0.01
ϕ	C-Firm maximum borrowing coefficient	10
ω_1	Weight of relative price in C-Firm competitiveness	20
ω_2	Weight of relative ability to satisfy demand in C-Firm competitiveness	1
ω_3	Parameter limiting size of period-to-period change in C-Firm market share	0.8
χ	Sensitivity of C-Firm market share to competitiveness	-1.467
τ^C	Tax rate on C-Firm profits	0.1
ξ_C	Share of loans C-Firms must repay at the end of a period	0.15
δ^C	C-Firm dividend payout rate	0.75
$\mathfrak{d}_K^1$	Lower bound of distribution for entering K-Firm deposits	0.425
$\mathfrak{d}_K^2$	Upper bound of distribution for entering K-Firm deposits	0.425
$\mathfrak{n}$	Parameter used to initialise brochures and revenues of entering K-Firms	10
$\mathfrak{f}$	Lower bound for market share below which a C-Firm exits	1e-5
$\mathfrak{f}^{entry}$	Parameter used to initialise market shares of entering C-Firms	0.0005
$\mathfrak{d}_C^1$	Lower bound of distribution for entering C-Firm deposits	0.1
$\mathfrak{d}_C^2$	Upper bound of distribution for entering C-Firm deposits	0.9
μ^{entry}	Initial mark-up of entering C-Firms	0.2
$\mathfrak{p}$	Shape parameter of Pareto distribution for initialisation of bank-firm network	0.8
$\mathfrak{p}_1^C$	Lower bound of Pareto distribution for initialisation of bank-C-Firm network	10
$\mathfrak{p}_2^C$	Upper bound of Pareto distribution for initialisation of bank-C-Firm network	35
$\mathfrak{p}_1^K$	Lower bound of Pareto distribution for initialisation of bank-K-Firm network	1
$\mathfrak{p}_2^K$	Upper bound of Pareto distribution for initialisation of bank-K-Firm network	4
CAR^*	Target capital adequacy ratio	0.05
RW_l	Risk weight on bank loans	1
$\mathfrak{M}$	Individual bank lending rate mark-up parameter	0.007
μ^B	Bank baseline loan rate mark-up	0.007
$\mathfrak{G}$	Banks' desired holdings of government Bonds as a fraction of outstanding loans	0.1
τ^B	Tax rate on bank profits	0.1
δ^B	Bank dividend payout rate	0.75

Table D1 – continued from previous page

Symbol	Description	Value
$\mathfrak{d}_B^1$	Lower bound for distribution of net worth of bailed out banks	1
$\mathfrak{d}_B^2$	Upper bound for distribution of net worth of bailed out banks	1
r	Central bank lending rate intercept[19]	0.04
$\underline{r}$	Central bank rate lower bound	1e-6
ι_1	Taylor rule smoothing parameter	0.777
ι_2	Taylor rule inflation sensitivity	1.186
ι_3	Taylor rule unemployment sensitivity	0.1
$\pi*$	Central bank target inflation rate	0.02015
$U*$	Central bank target unemployment rate	0.05
b^e	Energy sector payback period parameter	10
$\aleph^E$	Maximum lifespan of energy production plants	80
$\mathfrak{o}^e$	Fraction of energy sector revenue devoted to R&D	0.01
$\mathfrak{b}_1^E$	Parameter governing probability of innovation in energy technology	0.01
$\mathfrak{b}_2^E$	Shape parameter of beta distribution for energy technology innovation	3
$\mathfrak{b}_3^E$	Shape parameter of beta distribution for energy technology innovation	1.5
$\mathfrak{b}_4^E$	Lower bound for random energy technology innovation	-0.01
$\mathfrak{b}_5^E$	Lower bound for random energy technology innovation	0.005
δ^E	Energy sector dividend payout rate	0.99
δ^F	Fossil fuel sector dividend payout rate	0.01

Table D2: Economic model initial values

Symbol	Description	Value
LS_0	Initial labour force	25000
Pr_{κ_0}	Labour productivity of initial capital good vintages	1
EE_{κ_0}	Energy efficiency of initial capital good vintages	1
EF_{κ_0}	Environmental friendliness of initial capital good vintages	60
$Pr_{k,0}$	Labour productivity of initial K-Firm production techniques	0.0275
$EE_{k,0}$	Energy efficiency of initial K-Firm production techniques	0.0275
$EF_{k,0}$	Environmental friendliness of initial K-Firm production techniques	60
$TE\kappa_0^{de}$	Thermal efficiency of initial brown energy vintage	0.01
$c_{\kappa_0^{ge}}$	Per-unit expansion cost of initial green energy vintage	0.05
$TE\kappa_0^{de}$	Emission intensity of initial brown energy vintage	110
$D_{h,0}$	Initial household deposits	275000
$D_{e,0}$	Initial energy sector deposits	10000
$D_{k,0}$	Initial individual K-Firm deposits	500

[19] Annual

Table D2 – continued from previous page

Symbol	**Description**	**Value**
$D_{c,0}$	Initial individual C-Firm deposits	320
$NW_{B,0}$	Initial aggregate banking sector net worth	70000
A_0	Initial central bank advances	0
$\mathfrak{l}_{c,0}$	Initial individual C-Firm loans	470
w_0	Initial nominal wage rate	1
$\mathfrak{K}_{c,0}$	Initial individual C-Firm productive capacity	1320
$\frac{\mathfrak{K}_0^{ge}}{\mathfrak{K}_0^{ge}+\mathfrak{K}_0^{ge}}$	Initial share of green energy productive capacity	0.2
$p_{f,0}$	Initial fossil fuel price	1e-05
$\mu_{e,0}$	Initial energy sector mark-up	0.05
$\mu_{c,0}$	Initial C-Firm mark-up	0.2
$\tau_0^{Em,E}$	Initial emission tax rate on the energy sector	0.000025
$r_{CB,0}^l$	Initial central bank policy rate[20]	0.04

[20] Annual