A Heterogeneous Agents Model of Energy Consumption and Energy Conservation

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Abstract

In this paper, we investigate whether inflation-targeting monetary policy affects households' incentives to build resilience against energy price shocks. On the example of households' energy conservation decisions, we show how distributional aspects of monetary policy affect households' decisions to invest into technologies which decrease energy intensity. As labour market and asset ownership are the important indirect channels for the distributional effects of monetary policy in European countries, we utilize a stylized heterogeneous agents new Keynesian model with search and matching frictions in the labour market and nominal asset holdings. We modify the model to contain energy consumption and energy conservation capital. Monetary policy in the model affects labour market tightness, returns on the firm ownership and nominal bonds. In such a framework, calibrated to match households' income distribution, we further study heterogeneous and aggregate responses of energy conservation and energy consumption to monetary policy, rising energy prices and their interaction. We find that monetary policy influences consumption energy intensity. The influence comes from both the intertemporal elasticity of substitution and labour market allocations. The latter includes changes in the share of unemployed households, who cannot increase their energy conservation capital, and changes in the workers' precautionary motives when the labour market tightness changes. We further study different monetary policy responses to rising energy prices.

JEL Codes: E12, E24, E52, Q43, Q50.
Keywords: Consumption Energy Intensity, Heterogeneous Agents New Keynesian Models, Distributional Aspect of Monetary Policy.

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1. Introduction

Elevated energy prices and role of central banks in addressing climate change are currently important topics for macroeconomists and policy makers. While there is lively debate on whether central banks should explicitly address climate change, currently used policies can have indirect effects on environmental policies and energy conservation through distributional effects. Monetary policy reaction to energy prices can amplify or dampen effects of energy price shocks on different economic agents, stimulating or dampening their incentives to invest into energy conservation and to build resilience to energy price fluctuations.

In this paper, we contribute to the literature by investigating how conventional inflation-targeting monetary policy interacts with energy conservation decisions. It has been shown in the literature that monetary policy has distributional effects[1], while the data suggest that energy price shocks have heterogeneous impact on households[2]. Moreover, households can insulate from the energy price shocks by investing into the energy saving, or abatement, capital. Rising demand for the abatement capital creates additional revenues in related sectors. In our model, we consider how the possibility of abatement and heterogeneous effects of both energy price fluctuations and monetary policy, change monetary policy propagation in response to the energy price shocks. We show that distributional aspects of monetary policy affect investment into technologies reducing energy consumption. We further consider alternative monetary policy reaction functions in response to the energy price shocks.

We utilize a stylized heterogeneous agents new Keynesian (HANK) model with search and matching as in Ravn and Sterk (2021) and Challe et al. (2017), modified to contain energy in consumption and in production, and households‘ energy conservation capital. Monetary policy in the model affects labour market tightness, returns on nominal savings and on firm ownership. In such a framework, calibrated to match household income distribution, we further study individual and aggregate responses of energy conservation and energy consumption to monetary policy, rising energy prices and their interaction. The developed intuition regarding energy conservation decisions in our model framework can be extended to fuel consumption or investment into renewable energy.

Our results show that a restrictive monetary policy shock leads to a decrease in energy conservation capital and an increase in energy intensity of consumption. It increases the share of unemployed workers with limited investing possibilities and decreases incentives of employed workers to invest into energy capital when the returns on savings are larger and precautionary effects are stronger. As we assume that energy capital is produced domestically, depending on the manufacturing energy intensity, a rise in energy prices may have stimulative effects as it increases domestic demand for final good.

We further consider several types of monetary policy reaction to rising energy prices. In a standard monetary policy reaction function, we vary the coefficients of response to inflation and output. We find that when energy prices rise is expected and long-lived, the policies reacting to inflation stronger suppress inflation and output, investment in abatement capital and result in larger consumption energy intensity relative to policies with weaker response to inflation. We further calculate households‘ welfare for each type of the policy as a discounted infinite stream of consumption. After the energy price shock, for all the households groups the welfare is larger for the more accommodative policies.

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[1] For the analysis of distributional channels of monetary policy in euro area, see Slacalek et al. (2020).

[2] Energy share in household‘s expenditures varies with the household income, with the richest households having the smallest share of energy expenditures.

The results should be taken with caution as our model lacks the potential costs of prolonged high inflation - unanchoring of the inflation expectations nor inflationary spirals, which influences central banks‘ monetary policy decisions. We, however, believe that the results can be useful guidance in the environment with rational expectations and fully credible central bank.

Our framework builds upon HANK models[3] with endogenous labour market tightness and precautionary savings: Challe et al. (2017), Ravn and Sterk (2021). We draw upon the empirical works by Slacalek et al. (2020). The paper is also related to studies of distributional aspects of energy prices in Chan et al. (2022) and of energy conservation in response to the energy price shock Battistini et al. (2022), Pieroni (2023), Kilian (2008), Celasun et al. (2022).

When modelling energy consumption and abatement, we drew extensively from the general equilibrium models of energy consumption and emissions: Varga et al. (2022), Campiglio et al. (2022), Kiuila and Rutherford (2013). While these models focus on reducing carbon emissions, we adopt general formulation of abatement capital and energy consumption.

The paper is related to the debate on monetary policy reaction to rising energy prices and energy price shocks [4], in particularly to Auclert et al. (2023) who study fiscal and monetary policy responses to energy shocks but without abatement; as well as to the literature on the macroeconomic impact of change in energy prices[5]; and to a stream of models incorporating abatement capital.[6]

The paper is structured as follows. We first describe the model and the underlying assumptions. We then simulate the model response to monetary and energy price shocks to illustrate the mechanism behind the model's reaction. We then move to the analysis of different types of monetary policy rules and show the implications for the aggregate economy and different groups of households. We consider various scenarios for energy price development and show how different policy responses affect household's welfare and energy conservation decisions.

2. The Model: Incomplete and Preliminary

The underlying model is an extension of the models with imperfect insurance against unemployment risks and endogenous labour market tightness, Ravn and Sterk (2021) and Challe et al. (2017), to which we incorporate an energy service into the consumption bundle and the production function. Within each household, an energy service is made from the raw energy using household's "abatement" capital. A straightforward illustration of the energy service is heat generated within the house using the abatement capital - installed heating system and house insulation, while paying bills for the raw energy - electricity, gas, etc. Clearly, investing into better insulation, more efficient heating systems, including adding renewable sources of energy within the households, lowers the raw energy usage. At the same time such an investment is not affordable for the poorest, hand-to-mouth households.

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[3] For the seminal contributions to the HANK literature see Kaplan et al. (2018) or Violante (2021).

[4] Schnabel (2022), Natal (2012), Kormilitsina (2011).

[5] Forni et al. (2015), Kilian (2008).

[6] While integrated assessment models, i.e. Benmir et al. (2020) or Heutel (2012), focus on emissions as externalities and formulate abatement capital and costs in terms of reducing emissions, we focus on reducing energy consumption. Yet, in accordance with this literature, we formulate abatement capital in terms of domestic final goods.

2.1 Households

There is a unit mass of households, indexed by h. Each household consumes a composite good, $\mathbb{C}$, and holds the positions in the nominal bonds, B_H. Following the literature, we let a share ξ of the households be the firm owners, who are unproductive when employed. These households, whom we call capitalists, do not participate in the labour market and own all the firms and the production capital in this economy. The rest of the households, whom we call workers, supply a unit labour inelastically if employed. The employment is stochastic, where the share of $n_t \in (0,\xi)$ of households are employed, and $u_t = 1 - n_t - \xi$ are unemployed each period. The job destruction rate ω is exogenous, job finding rate η_t is endogenously determined by firms' demand for labour.

Each household maximizes the infinite sum of expected utility over the composite consumption good $\mathbb{C}$ taking into account expected employment status and discount factor β. We allow for different discount factor for the workers and for the capitalists. The capitalists' discount factor is further modelled to be an endogenous function of the current capital stock. We will discuss this assumption in more details when characterising the agents' equilibrium behaviour.

$$U_t(h) \equiv E_t \sum_{j=0}^{\infty} \beta^j \frac{\mathbb{C}_{t+j}(h)^{1-\mu}}{1-\mu}, \tag{2.1}$$

where μ is the degree of relative risk aversion. The composite consumption good consist of energy services, E^s, and non-energy consumption good, C, combined in a constant elasticity of substitution index:

$$\mathbb{C}_t(h) = \left[(1-\phi_e)^{\frac{1}{\lambda_e}} C_t(h)^{\frac{\lambda_e - 1}{\lambda_e}} + \phi_e^{\frac{1}{\lambda_e}} E_t^s(h)^{\frac{\lambda_e - 1}{\lambda_e}} \right]^{\frac{\lambda_e}{\lambda_e - 1}}, \tag{2.2}$$

where parameters ϕ_e and λ_e reflect the equilibrium share of energy in the household consumption and limited substitution between the energy and non-energy goods in the short to medium term.

Households obtain energy services $E_t^s(h)$ from raw energy $E_t^r(h)$ using their last period abatement capital $K_{t-1}^e(h)$ which helps them to reduce their raw energy consumption:

$$E_t^r(h) = \frac{1}{f(K_{h,t-1}^e)} E_t^s(h), \tag{2.3}$$

were the abatement function $f(K_{h,t-1}^e)$ is convex in the abatement capital, but has decreasing returns to scale: $f'(K_{h,t-1}^e) > 0$ and $f''(K_{h,t-1}^e) > 0$.

An employed household gets nominal wage $W_t(h) = W_t$, an unemployed gets nominal benefits $P_t W_{\mu,t}$ fixed in real terms, a firm owner receives the dividends and return on capital. Employed workers and capitalists pay income tax with rate τ_t. Denoting aftertax household income as $\tilde{W}(h)$ depending on the household type, one can write a household's budget constraint as (household subscripts are dropped):

$$P_t C_t + P_t^e E_t^r + B_t + \frac{\psi_b}{2} \left(\frac{B_t}{\bar{B}} - 1 \right)^2 P_t B_t + P_t^I I_t + P_t^I I_t^e \leq \tilde{W}_t + R_{t-1} B_{t-1}, \tag{2.4}$$

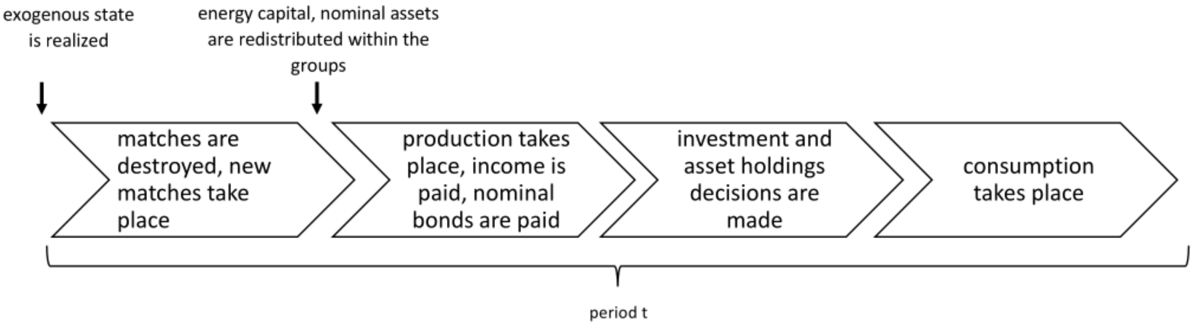
where on the revenue side of the budget constraint, there is an income - labour income, unemployment benefits or capitalists revenues; and the return on nominal bonds, B_{t-1}. If the household is a borrower on the bond market, the return enters with a negative sign. On the expenditure side, there is consumption of goods and raw energy, nominal bond holdings, portfolio adjustment costs in units of a final good, investment into capital (only for the capitalists) and into abatement capital. Investment into both types of capital is made in units of domestic final good with the price $P_t^I = P_t$. Energy price P^e is an exogenous process and raw energy is in unlimited supply form the rest of the world.

For model tractability, we employ a convenient assumption from Challe et al. (2017) that all households are grouped in identical "families" of the same size. As the probability of changing employment status is the same across families, all the families have the same expected share of employed workers, and unemployed workers with different duration of being unemployed. Within the families there is a distribution of agents with different asset holdings history. As in Challe et al. (2017) we allow for risk-sharing among the employed family members, that is, all the bonds are averaged between currently employed households. Such an assumption simplifies the model solution substantially, while generating endogenous precautionary savings.

We further assume that workers are moving across employed and unemployed residences when their employment status changes, and they can not take their abatement capital with them. Their current level of abatement capital is absorbed by the government, who provides every newcomer to the residence with the same level of abatement capital as other residents have. That is, the when a former unemployed worker enters the employed pool, they enjoy the same level of abatement capital as the rest of the employed workers. The employed workers, when investing into the abatement capital, take into account the probability of becoming unemployed and leaving the employed residency. Thus the abatement capital does not play a role of a precautionary asset.

The timeline for the model is in Figure 1. At the beginning of the period, the exogenous state is realized, the matches between the firms and the workers are exogenously destroyed and the firms decide how many workers to hire. The new matches take place; with the new employment status, there is a redistribution of nominal assets among employed workers, and abatement capital levels among the corresponding residencies. The production takes place using the last period investment and the income is paid. Afterwards, households make their investment and consumption decisions. At the end of the period consumption takes place.

Figure 1: Timeline



The family head than solves consumption and assets holding problem (in Appendix A), while caring equally for all family members. We show in Appendix that only the employed workers choose to save with their intertemporal elasticity of substitution $IMRS = 0$, while others groups, including first-period unemployed, would like to borrow with the $IMRS < 0$. This also implies that the first-period unemployed workers have preferences for consuming all their precautionary savings during a single period. By setting the borrowing limit for unemployed workers to zero and for capitalists to $\bar{b}^c < 0$, we limit the distribution of households to four groups: employed, newly unemployed, long-term unemployed, and capitalists.

Employed workers are non-constrained households in the model, who have nominal savings and invest into the abatement capital. As shown in the Appendix A, both unemployed worker types are poor hand-to-mouth, who choose not to invest into abatement capital and do not have nominal debt.

Capitalists invest into abatement and productive capital. They do not have precautionary motives and the equilibrium interest rate on nominal credit is attractive for them. Therefore they become rich borrowers - rich hand-to-mouth agents which absorb households' equilibrium nominal savings. Out of the equilibrium we allow for the dis-match of domestic nominal savings and borrowings in line with the open economy assumption. So that the excessive borrowings or savings are absorbed by the rest or the world. Presence of the rest of the world credit out of the equilibrium path, requires additional assumptions in order to close the model. We use the results from the Schmitt-Grohe and Uribe (2003) and incorporate portfolio adjustment costs for employed workers, defined above, and endogenous discount factor for the capitalists.

The capitalists become more patient when the current level of aggregate capital k_{t-1} falls short of its steady value, and become less patient when the current capital rises above it steady state level:

$$\beta_t^c = \beta \left(\frac{k_{t-1}}{\bar{k}} \right)^{-\psi_k \beta}, \tag{2.5}$$

where β is the constant discount factor of workers, ψ_k - parameter governing elasticity of capitalists discount factor with respect to current level of capital. The capitalists do not internalize the effect their capital investment have on their discount factor.

2.2 Good Producers

Goods producers are monopolistic producers of differentiated intermediate goods. In the production function, producers use domestic capital K, domestic labour N and raw energy input E^{rp}. In this paper, we abstract from producers' incentives for energy conservation and fix share of energy used in production at ρ_o. This assumption can be further motivated by limited possibilities of producers to adjust their energy usage within the monetary policy horizon.[7] We formulate production function as Leontief technology:

$$Y_t \;=\; min\left[\frac{1}{1-\rho_o} A_t N_t^{1-\gamma_k} K_{t-1}^{\gamma_k}, \frac{1}{\rho_o} E_t^{rp} \right]. \tag{2.6}$$

The producers price their output in the Rotemberg pricing tradition with the pricing cost parameter ϕ. The producer pay vacancy costs κ in units of final goods produced. The marginal costs and the

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[7] Hassler et al. (2021) find elasticity of the US be rather low - 0.02.

result of Rotemberg pricing are formulated as:

$$
\begin{aligned}
mc_t &= \frac{1-\rho_o}{mpl_t}\left(w_t+\kappa/q_t-(1-\omega)\beta_{c,t}E_t\Lambda_{t,t+1}\left[\kappa/q_{t+1}\right]\right)+\rho_o P_t^e, && (2.7)\\
\gamma mc_t &= \phi(\Pi_t-1)\Pi_t-\phi\beta_{c,t}E_t\left(\frac{C_{c,t}}{C_{c,t+1}}\right)^{-\mu}(\Pi_{t+1}-1)\Pi_{,t+1}\frac{Y_{t+1}}{Y_t}+\gamma-1, && (2.8)\\
E_t\Lambda_{t,t+1} &= E_t\left(\frac{\mathbb{C}_{c,t+1}}{\mathbb{C}_{c,t}}\right)^{-\mu}, && (2.9)\\
q_t &= \eta_t^{\frac{\alpha}{\alpha-1}}. && (2.10)
\end{aligned}
$$

The firms select the optimal inputs and output levels, taking prices as given. The first-order conditions imply:

$$
Y_t(i)=\left(\frac{P_t(i)}{P_t}\right)^{-\gamma}Y_t, \tag{2.11}
$$

where the prices are determined by demand from households, with $P_t=\left(\int_0^1 P_t(i)^{1-\varepsilon}di\right)^{\frac{1}{1-\varepsilon}}$.

The final good producers sell the final goods to households.

2.3 Aggregation and Monetary Policy

The get the total labour supply in this economy, consider how does the distribution of employment evolves. Denote N_t and U_t as number of employed and unemployed. Then:

$$
\begin{aligned}
N_{t+1} &= N_t(1-\omega(1-\eta_{t+1}))+U_t\eta_{t+1}, && (2.12)\\
U_{t+1} &= 1-N_{t+1}-\xi. && (2.13)
\end{aligned}
$$

Output in each economy is used for consumption, payment for raw energy from abroad, investment into capital and abatement capital, payments for vacancy costs and adjustment costs. The resource constraint in real terms then takes the form:

$$
Y_t = C_t+\tilde{P}_t^e(E_t^r+E_t^{rp})+I_t+I_{e,t}+Y_t\kappa/q_t+\frac{\psi_b}{2}\left(\frac{\tilde{B}_{e,t}}{\bar{B}}-1\right)^2\tilde{B}_{e,t}N_t, \tag{2.14}
$$

Note, that the investment into abatement capital is formulated in terms of final good, similarly to Benmir et al. (2020) or Heutel (2012). That is, larger investment increases demand for final good and can be stimulative.

The unemployment benefits are compensated with tax collection in the future. The tax is collected from employed workers and capitalists dividends.

$$
\tau_{t+1}=\frac{W_\mu U_t}{W_tN_t+(div_t-i_t)\xi}. \tag{2.15}
$$

There is a central bank that sets the nominal interest rate using the following baseline rule:

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\rho_r} \left[\left(\frac{E_t \Pi^p_{t+1}}{\bar{\Pi}}\right)^{\phi_\pi} \left(\frac{Y_{t+1}}{\bar{Y}}\right)^{\phi_y}\right]^{1-\rho_r} \varepsilon^r_t. \tag{2.16}$$

In the rule above, the central bank adjusts the policy rate relative to its steady-state value, $\bar{R}$, responding to the expected deviations of future policy inflation Π^p from the target, $\bar{\pi}$, and to the expected deviations of output Y from its steady state level $\bar{Y}$. The strength of the response is governed by parameters ϕ_π and ϕ_y. In the rule, there is a stochastic AR(1) process, ε^r, with i.i.d. shock μ^r_t and persistence ρ_r.

The policy inflation is weighted average of energy price inflation and consumer price inflation:

$$\Pi^p_t = \Pi_t \left(\frac{\tilde{P}_{e,t}}{\tilde{P}_{e,t-1}}\right)^{\phi_e}, \tag{2.17}$$

where $\tilde{P}^e_t$ is the price of raw energy normalized by the price of consumer good P_t and $\Pi_t = P_t/P_{t-1}$ is consumer price inflation. The policy inflation reflects the composition of consumption bundle by using a share of energy service in consumption bundle ϕ_e as a weight on energy price inflation.

In the simulation below we vary the policy rule to demonstrate the effects of monetary policy on energy conservation.

3. Equilibrium

TBA

4. Calibration

Some of the standard parameters we take from the literature (e.g Ravn and Sterk 2021) as discussed in Appendix C. The parameters specific to our model include energy related ϕ_e, λ_e, δ_e. We set $\phi_e = 0.15$ to match the 15% share of energy consumption in the final consumption expenditures. Energy capital depreciation rate $\delta_e = 0.01$ is set to match 4% depreciation per year.[8]. In the baseline simulation, we chose the share of energy in production function $\rho_o = 5\%$, we later discuss the implications of energy accounting for 1% and 10% of production (TBA). We set elasticity of substitution between energy and non-energy consumption goods λ_e to be 0.3 in accordance with the literature (de Walque et al. 2017 and Natal 2012).

Labour market specific parameters - steady state job finding rate, $\bar{\eta} = 0.15$, was set to reflect the share of unemployed (poor hand-to-mouth, HtM, consumers) 11%, and share of capitalists ξ is set to be 10% to match the corresponding share of capitalists in the population. We calculate ratios of workers' savings to their income and capitalists' debt to their income using Household Finance and Consumption Network (2023).[9]

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[8] As our energy capital is housing specific product, we set full depreciation period to be 25 years similar to housing products and heating systems.

[9] The shares are calculated using the following series. TBA

We set price duration to have the equivalence of Calvo probability 0.82 as estimated posterior mode for price rigidities in New Area Wide Model II (see Coenen et al. 2018), the Taylor rule persistence parameter is fixed at 0.93 as estimated posterior mode for interest rate smoothing from New Area Wide Model II.

To calibrate adjustment costs we roughly match the the volatilities of 0.03 of the output growth and aggregate consumption growth in response to the 0.35 pp interest rate shock in the CNB core forecasting model (Brazdik et al., 2020) during the first 8 quarters.

We calibrate abatement parameter to match the steady state share of energy expenditures among the workers at 15%.

Table 1: Calibrated Parameters

Name	Symbol	Value
Energy consumption:		
Share of energy in CES aggregator	ϕ_e	0.15
Steady state ratio of employed and unemployed share of energy consumption	θ^e	0.75
Elasticity of substitution	λ_e	0.3
Energy capital depreciation	δ_e	0.01
Energy share in output	ρ_o	0.05
Labour market:		
Steady state job finding rate	$\bar{\eta}$	0.15
Share of firm owners	ξ	0.1
Financial variables:		
Borrowing limits for unemployed workers	$\bar{b}_e$	0
Adjustment costs:		
Portfolio adjustment costs’	ψ_b	0.01
Capitalists’ discount factor adjustment	ψ_k	0.5
Abatement parameter	$1/\psi_{ab}$	0.04
Other variables:		
Steady state tax ratio	τ	0.15
Price duration		6 quarters

We further use Table 2 to compare the resulting steady state values with the data.

Table 2: Matched Steady-State Ratios and the Data

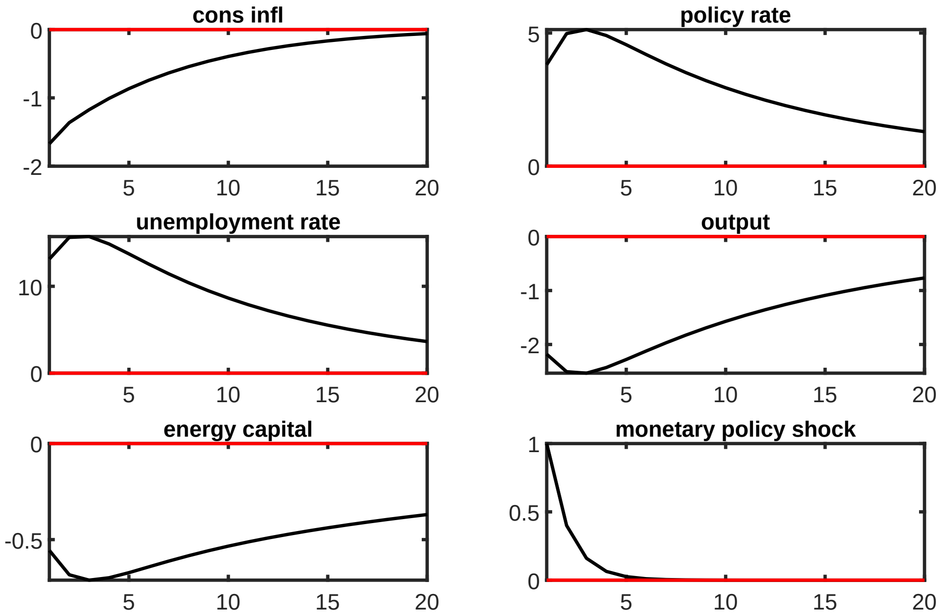
Name	Symbol	Value	
		Model	Data
Steady state workers’ propensity to save	$\bar{B}_t/\overline{Income}$	0.29	0.29
Capitalists debt-to-income ratio	$-\bar{b}^c/\overline{Rev}$	0.68	0.7
Steady state share of workers energy expenditures	$\bar{E}_e^r/(\bar{E}_e^r+\bar{C}_e)$	0.15	0.15

5. Simulations

In this section we simulate the model, linearised around a non-stochastic steady state, to demonstrate how the shocks propagate through the model with the closer analysis of distributional effects of monetary policy and energy price shocks.

Figure 2 shows impulse responses of the aggregate variables to an unexpected monetary policy shock. Rising policy rate suppresses inflation and output, leading to an increase in unemployment. Aggregate energy capital falls due to a fall in capital holdings of employed workers and capitalists and an increasing share of unemployment workers who choose not invest in energy capital.

Figure 2: Impulse Responses to a 1% Positive Monetary Policy Shock

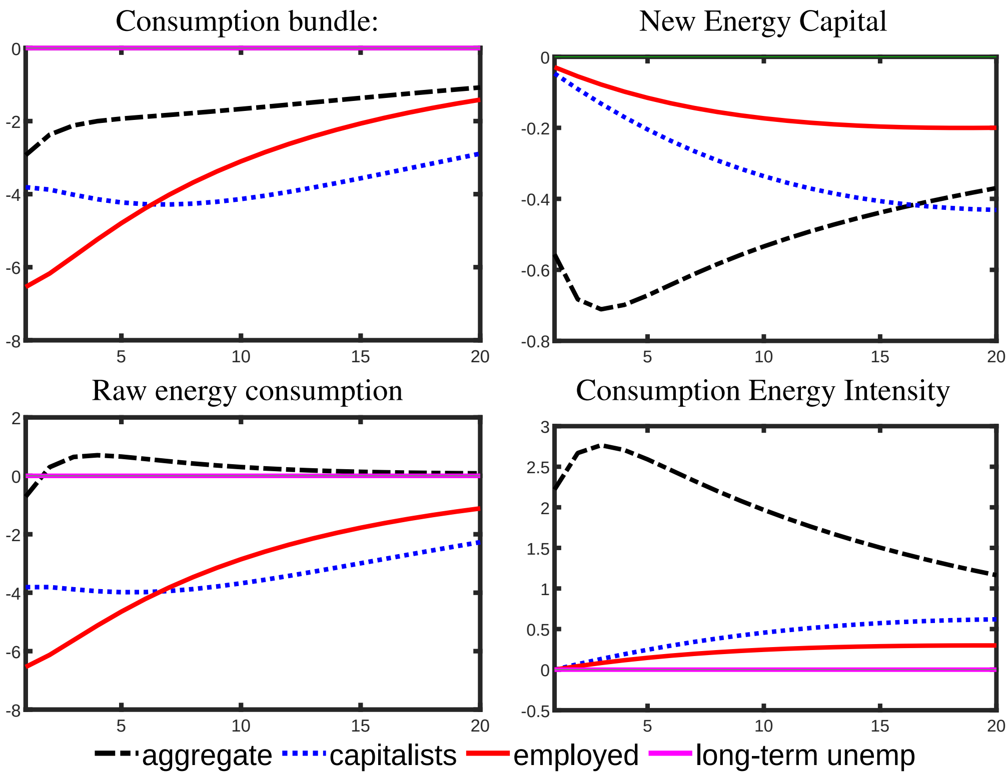


Note: All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state

To study the dynamics of energy usage, we introduce a measure of consumption energy intensity as a ratio of raw energy used for a unit of final consumption $E^r/\mathbb{C}$. Note that the final consumption $\mathbb{C}$ includes energy service as a function of energy capital. That is, the consumption energy intensity reflects both how effectively raw energy is used in producing the energy services and the limited substitution between energy and non-energy good. A rise in the energy intensity indicates that the energy is used less efficiently as the agents use more raw energy for a consumption unit, a fall in this index indicates more efficient energy usage by the households.

In Figure 3, we show the responses for different groups of households and for aggregate variables for 1% unexpected rise in monetary policy rate. Employed workers are the only agents in the economy with the binding consumption Euler equation and with the functioning intertemporary elasticity of substitution channel. With the increase in interest rate, they reduce their consumption and save more. Also job-finding rate falls which intensifies their incentives for precautionary savings. Long-term unemployed workers have their benefits fixed in real terms and do not change their consumption pattern in response to a monetary policy shock. Capitalists, who are borrowers, suffer from an increase in the interest rate and reduce their consumption. Note that aggregate variables are weighted averages for all the groups, they do not only reflect the choices of each group, but also the size of the group. As the pool of unemployed workers increases, the aggregate variables reflect unemployed workers' choices more. When it comes to energy capital, unemployed workers choose not to adjust it. Employed workers reduce their energy capital holdings as the savings become more attractive. Capitalist decrease their energy capital holdings as their debt service becomes more expensive. The aggregate fall in energy capital is large as there are more unemployed workers with low energy capital holdings. Raw energy consumption, after small initial fall, rises due to the changes in the consumption and change in the abatement capital levels. To disentangle these two effects, we plot consumption energy intensity. Energy intensity rises for all the groups and even more in the aggregate, reflecting an increase in the consumption energy intensity in response to the monetary policy shock. There is no change in energy intensity for unemployed workers, but as there more of them in the economy, the aggregate energy intensity rises, reflecting larger steady state energy intensity for unemployed workers.

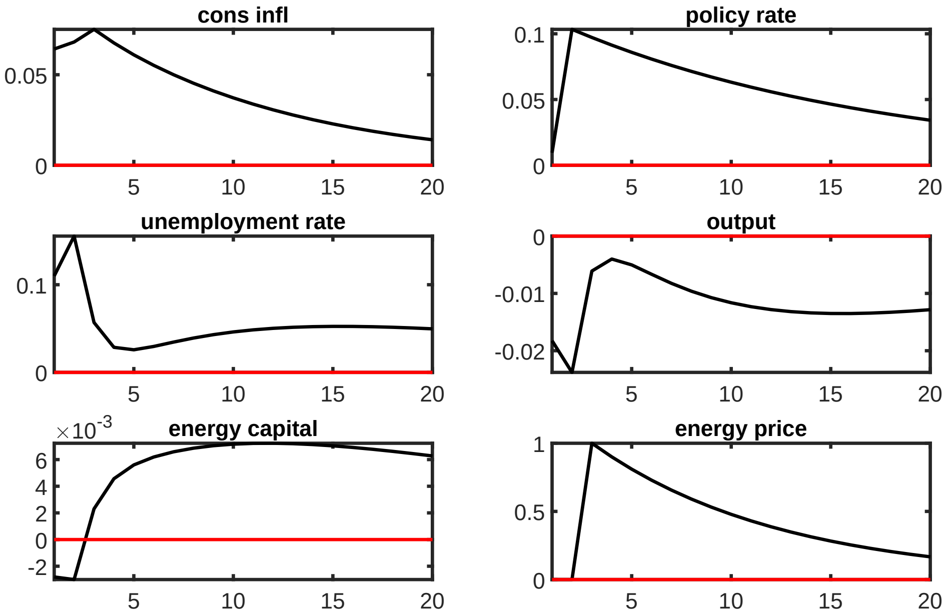
Figure 3: Effects of Heterogeneity, 1% positive monetary policy shock



Note: All responses are reported as percentage deviations from the steady state.

We further consider impulse responses to an expected persistent energy price shock in Figure 4. We choose such a process for the energy price shock, which would cause an increase in the policy relevant inflation. At period 1 arrives the news about a shock, which is to happen at period 3. As energy is a part of the production function, a rise in marginal costs of production pushes the consumer price inflation up and policy rate inflation reflects both rising energy and domestic prices. Producers expecting rising production costs reduces their hiring and increase domestic prices once the news arrives. There is increase in unemployment and a fall in demand accompanied by the higher inflation and policy rates before the energy prices rise. When the energy prices rise, there is a stronger incentive to invest into energy capital by the employed workers and capitalists. As energy capital is produced with domestic final good, a stronger demand for energy capital somewhat stimulates domestic output and employment.

Figure 4: Impulse Responses to a 1% Expected Energy Price Shock

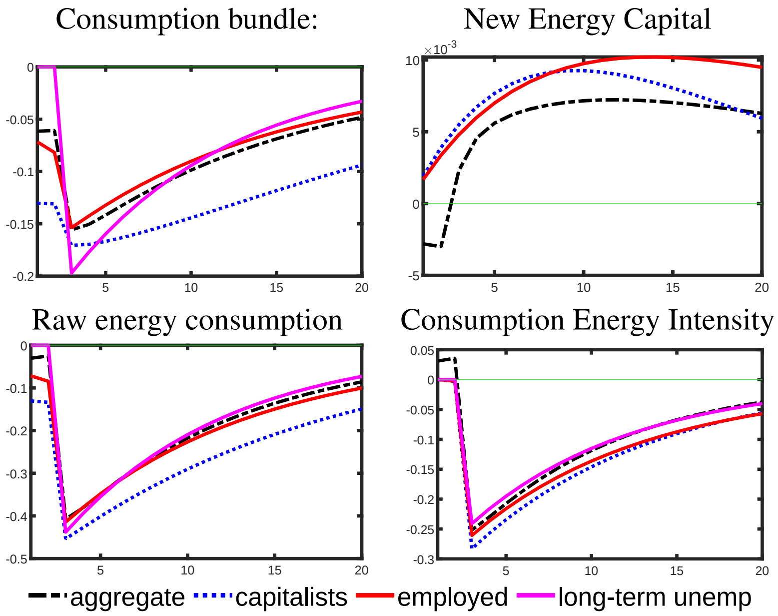


Note: All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state

Looking at distributional effects of rising energy prices in Figure 5, when energy prices actually rise, consumption of the poorest - unemployed workers, is affected the most. These are the poor hand-to-mouth workers, without the possibility to invest into abatement capital to smooth their consumption. Unemployed workers decrease their consumption, and decrease the consumption of the expensive raw energy. As the consumption aggregate features limited substitution between energy and non-energy goods, employed workers lower their consumption, yet, on a smaller scale than unemployed workers. The capitalists are sensitive to a rise in the interest rates, and reduce their consumption as soon as interest rate rises. Both employed workers and capitalists start to accumulate more energy capital as soon as news about rising energy prices arrive. Raw energy consumption falls for all the groups, with the larger fall for unemployed workers. Energy intensity falls for all the groups. The larger fall is observed for capitalists as they invest more into energy capital. The smaller fall is for unemployed workers, who can only save energy by consuming it less.

To sum up, our simulations show that monetary policy shocks can result in increase in energy intensity, and heterogeneity plays an important role in their propagation. We also show how movements in policy rate influence propagation of energy price shocks. In next section, we consider the different types of policy rules and analyse their role in the economy and in energy conservation decisions in presence of energy price shocks.

Figure 5: Effects of Heterogeneity, 1% Expected Energy Price Shock



Note: All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state.

6. Policy Analysis

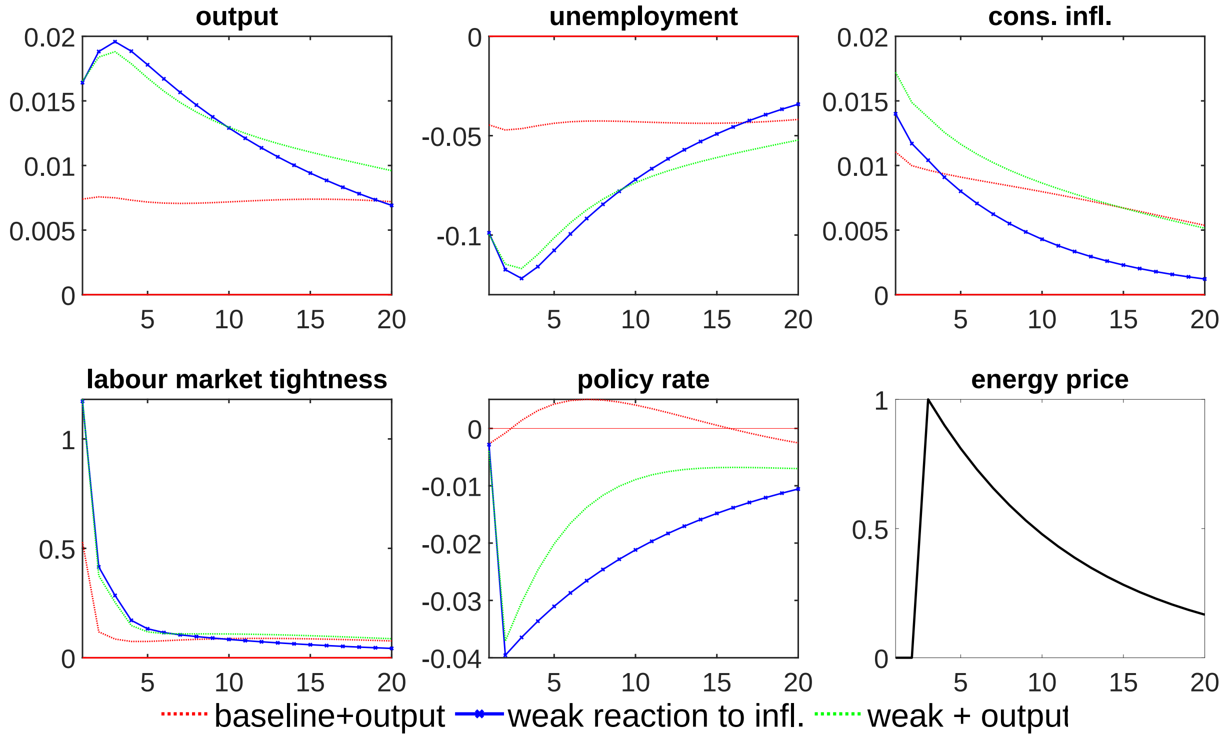
In this section we consider the effects of different policy responses to rising energy prices. In particular, we are interested in the response of the aggregate consumption energy intensity. When energy price rises, it is expected that the agents will invest more into the abatement capital. The question, we are interested in, if the different policy rules can fuel or mitigate this incentive through distributional channels of monetary policy, in particular, labour market channel and through the agents' nominal asset holdings.

The persistence of the energy price shocks, and how strongly these shocks have propagated to the consumer price inflation change both economic outlook and monetary policy implications. If a shock is not expected to have prolonged and significant impact on policy relevant inflation, it is reasonable for a central bank not to react to it. In the opposite case, it can be desirable for a monetary authority to increase policy rates in response to rising inflation. But the policy trade off arises potentially between stimulating inflation and output. That is why we consider an expected and persistent energy price shock which results in stronger energy prices propagation to the economy. To highlight the monetary policy effects, we consider several scenarios, in which monetary policy reacts to inflation with different strength or reacts to output. Other words, we consider rules with different parameters in (2.16), such that these parameters are constant over time and agents have full information rational expectations about both the parameters and future economic variables.

In Figures 6-7, we consider a baseline policy rule a pure inflation targeting rule with the reaction to inflation $\phi_\pi = 2$ and reaction to output $\phi_y = 0$ as used in the section before. We further consider "baseline+output" rule with a positive coefficient on output in (2.16): $\phi_\pi = 2$ and $\phi_y = 0.9$ as "baseline+output" line; a rule with weak reaction to inflation $\phi_\pi = 1.2$ and $\phi_y = 0$ as "weak" line and a "weak+output" with $\phi_\pi = 1.2$ and $\phi_y = 0.9$. In Figures we report the differences in responses relative to the baseline policy rule. A positive difference means that a response is larger under baseline rule.

In Figure 6, the policies which react to inflation weaker generally result in a smaller recession in terms of output and unemployment. Furthermore, they stimulate investment into abatement capital, which puts upward pressure on the output. Figure 7, shows the responses of consumption energy intensity and energy capital relative to the baseline policy rule. While the differences are not dramatic, the policy rule with a weaker policy response and higher employment support results in smaller energy intensity and larger energy capital holdings in the medium term.

Figure 6: Policy Responses, 1% Expected Energy Price Shock



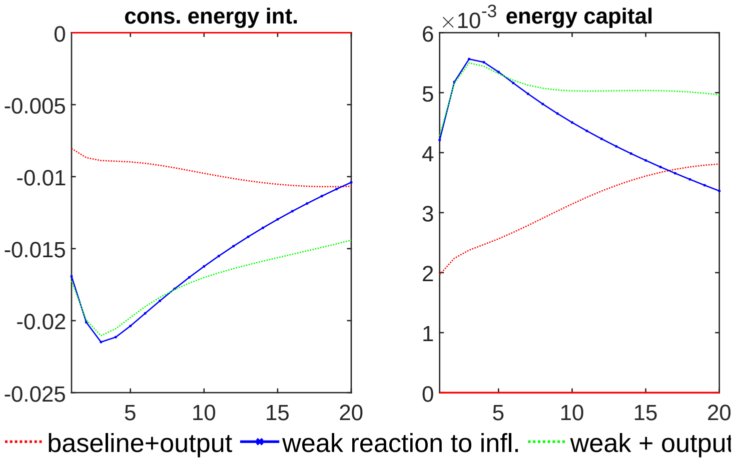
Note: All responses are reported as percentage points difference relative to the baseline policy, except for exogenous energy price shock which is in per cents. Positive values mean the reaction is larger than under the baseline policy.

6.1 Welfare analysis

It can be instructive to consider welfare effect of the central bank policies in response to energy shocks on different agents. To do this, we calculate welfare as discounted infinite stream of utility for every group of households, where for workers, job-finding rate enters their probability to be employed in the future periods. The simulations in Figure 8 show the welfare responses in differences from baseline policy rule. The capitalist welfare is larger for the policy rate which results in higher output and smaller interest rate, for all types of workers, the welfare is larger for the policy with the largest job-finding rate. For all types of agents, this is the policy with weak reaction to inflation and output support. It is not straightforward to consider the social welfare in a model with heterogeneous agents, but as an average indicator one can calculate an aggregate - consisting of all agents welfare weighted by their relative share. Such an indicator suggests that a weak reaction to energy price inflation and output support can be somewhat preferable in terms of the welfare.

To sum up, in our simple model framework with distributional aspects of monetary policy working though both direct - intertemporal elasticity of substitution, and indirect - labour market tightness

Figure 7: Policy Responses Con't, 1% Expected Energy Price Shock



Note: All responses are reported as percentage points difference relative to the baseline policy. Positive values mean the reaction is larger than under the baseline policy.

and changes in precautionary savings, there is an interaction between monetary policy and household investment into reducing their consumption energy intensity. The distributional effects depend on the presence of hand-to-mouth households, who can not increase their level of abatement capital, and on precautionary savings of workers, who increase their saving more when facing higher probability of being unemployed[10] or when the interest rates are higher.

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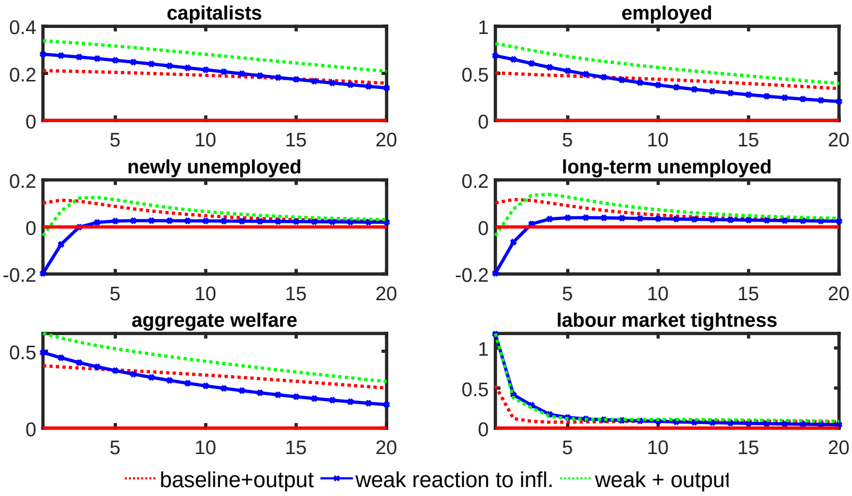
[10] The probability of being unemployed depends on the exogenous separation rate and the endogenous probability of find a new job.

Figure 8: Policy Responses: Welfare, 1% Expected Energy Price Shock



Note: All responses are reported as percentage points difference relative to the baseline policy. Positive values mean the reaction is larger than under the baseline policy.

7. Conclusion

In this paper, we show that monetary policy influences energy conservation decisions through its distributional effects. By changing labour market tightness, it affects agents' precautionary motives and share of unemployed workers with limited abilities to invest into energy saving.

We extend a stylized HANK model with the energy product in the households consumption bundle and in the production function. We further add energy capital which reduces the consumption of raw energy. In the model, energy price shock affects both households' demand and firms' supply. Such a framework is helpful to analyse different policy responses to energy price shocks. We consider several types of policies depending on the strength of reaction to inflation and to the output in the policy rule. When raw energy prices change, all agents have incentives to invest into energy saving capital. We find that rising policy rates on the other hand, can dampen these incentives by suppressing creation of new jobs, increasing amount of unemployed workers and rising returns on nominal savings. At the same time, our framework studies the economy under full information rational expectations and does not allow either for wage-price spirals nor for unanchoring of inflation expectations, which can increase economic costs of inflation. As such, our results should be taken with caution.

Appendix A: Solution to Households' Problem

In the model, the distribution of agents collapses to four groups: employed workers, first-time unemployed, long-term unemployed and capitalists. As long-term unemployed we understand workers who have been unemployed for longer than one period. It is convenient to solve the problem for each group separately. First, we re-write general households' budget constraint in real terms by dividing both sides by the price of consumption good P_t. For convenience, we denote relative prices and wages as $\tilde{P^e}$ and $\tilde{W}$, and real bond as $\tilde{B}$. We define the domestic inflation as $\Pi_{t+1} \equiv \frac{P_{t+1}}{P_t}$.

$$C_t + \tilde{P}^e_t E^r_t + \tilde{B}_t + \frac{\psi_b}{2}\left(\frac{\tilde{B}_t}{\bar{\tilde{B}}} - 1\right)^2 \tilde{B}_t + I_t + I^e_t \leq \tilde{W}_t + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{t-1}. \tag{A.18}$$

The family head optimizes workers allocations taking into account possible changes in their employment status. We denote choices for employed workers as C_e, first period unemployed workers as C_{eu}, and long-term unemployed workers as C_{uu}. The probability for an unemployed worker to find a job is the job-finding rate η_t. The probability of an employed worker to become unemployed equals probability to loose the job, ω, and not to find the match at the beginning of the same period $1-\eta_t$: $\omega(1-\eta_t)$. The probability of an employed worker to stay employed is the opposite of losing the job: $1-\omega(1-\eta_t)$. Note, that the level of abatement capital is the same for all types of unemployed workers. We denote this level as $k^e_{u,t}$ for unemployed workers, and $k^e_{e,t}$ for employed workers.

The employed workers are unconstrained agents. They do not own firms and do not invest into physical capital. The Lagrangian is formulated as

$$\begin{aligned} L \equiv & \max_{C_{e,t}, E^r_{e,t}, \tilde{B}_{e,t}, I^e_{e,t}} E_t \sum_{t=0}^{\infty} \beta^t U_t + \\ & \lambda_{bc}(\tilde{W}_t + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{e,t-1} - C_{e,t} - \tilde{P}^e_t E^r_{e,t} - \tilde{B}_{e,t}(1 + \frac{\psi_b}{2}\left[\frac{\tilde{B}_{e,t}}{\bar{\tilde{B}}} - 1\right]^2) - I^e_{e,t}), \end{aligned} \tag{A.19}$$

with the following Kuhn-Tucker conditions:

$$\begin{aligned} [\frac{\partial L}{\partial I^e_{e,t}}]: \quad & -\lambda_{bc}\left(\frac{1-\phi_e}{\phi_e}\right)^{\frac{1}{\lambda_e}} \mathbb{C}_{e,t}^{-\mu}\left(\frac{\mathbb{C}_{e,t}}{C_{e,t}}\right)^{\frac{1}{\lambda_e}} + \\ & +\beta\left[(1-\omega(1-\eta_{t+1}))\mathbb{C}_{e,t+1}^{-\mu}\left(\frac{\mathbb{C}_{e,t+1}}{E^s_{e,t+1}}\right)^{\frac{1}{\lambda_e}} E^r_{e,t+1} f'(k^e_{e,t}) + \right. \\ & \left. + \,\omega(1-\eta_{t+1})\mathbb{C}_{eu,t+1}^{-\mu}\left(\frac{\mathbb{C}_{eu,t+1}}{E^s_{eu,t+1}}\right)^{\frac{1}{\lambda_e}} E^r_{eu,t+1} f'(k^e_{u,t})\right] \leq 0, \\ & I^e_{e,t}\frac{\partial L}{\partial I^e_{e,t}} = 0, \end{aligned} \tag{A.20}$$

$$\begin{aligned} & [\frac{\partial L}{\partial \tilde{B}_{e,t}}]: \quad -\lambda_{bc}\mathbb{C}_{e,t}^{-\mu}\frac{\mathbb{C}_{e,t}}{C_{e,t}}^{\frac{1}{\lambda_e}} + \beta E_t \frac{R_t}{\Pi_{t+1}}\left[(1-\omega(1-\eta_{t+1}))\mathbb{C}_{e,t+1}^{-\mu}\left(\frac{\mathbb{C}_{e,t+1}}{C_{e,t+1}}\right)^{\frac{1}{\lambda_e}} + \right. \\ & \left. +\omega(1-\eta_{t+1})\mathbb{C}_{eu,t+1}^{-\mu}\left(\frac{\mathbb{C}_{eu,t+1}}{C_{eu,t+1}}\right)^{\frac{1}{\lambda_e}}\right] \leq 0, \\ & \tilde{B}_{e,t}\frac{\partial L}{\partial \tilde{B}_{e,t}} = 0, \end{aligned} \tag{A.21}$$

$$\lambda_{bc}(\tilde{W}_{e,t} + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{e,t-1} - C_{e,t} - \tilde{P}_t^e E_{e,t}^r - \tilde{B}_{e,t} - \frac{\psi_b}{2}\left[\frac{\tilde{B}_{e,t}}{\bar{\tilde{B}}} - 1\right]^2 - I_{e,t}^e) = 0, \tag{A.22}$$

$$\tilde{W}_{e,t} + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{e,t-1} - C_{e,t} - \tilde{P}_t^e E_{e,t}^r - \tilde{B}_{e,t} - \frac{\psi_b}{2}\left[\frac{\tilde{B}_{e,t}}{\bar{\tilde{B}}} - 1\right]^2 - I_{e,t}^e \geq 0. \tag{A.23}$$

For the unconstrained, employed, workers, $I_{e,t}^e > 0$, $\tilde{B}_{e,t} > 0$ and the budget is exhausted. The consumption-saving and abatement capital investment decisions are determined by setting to zero (A.21) and (A.20) respectively.

The relationship between energy and consumption good is given by the expenditure minimization problem:

$$\frac{C_{e,t}}{E_{e,t}^s} = \frac{1-\phi_e}{\phi_e}\left(\frac{P_{e,t}}{f\left(k_{e,t-1}^e\right)P_t}\right)^{\lambda_e}. \tag{A.24}$$

For both types of unemployed workers $j = \{eu, uu\}$ the problem can be formulated as follows:

$$\begin{aligned} L \equiv & \max_{C_{j,t}, E_{j,t}^r, \tilde{B}_{j,t}, I_{j,t}^e} E_t \sum_{t=0}^{\infty} \beta^t U_t + \\ & \lambda_{bc}(\tilde{W}_\mu + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{j,t-1} - C_{j,t} - \tilde{P}_t^e E_{j,t}^r - \tilde{B}_{j,t}(1 + \frac{\psi_b}{2}\left[\frac{\tilde{B}_{j,t}}{\bar{\tilde{B}}} - 1\right]^2) - I_{j,t}^e), \end{aligned} \tag{A.25}$$

$$\begin{aligned} [\frac{\partial L}{\partial I_{j,t}^e}]: \quad & -\left(\frac{1-\phi_e}{\phi_e}\right)^{\frac{1}{\lambda_e}} \mathbb{C}_{j,t}^{-\mu}\left(\frac{\mathbb{C}_{j,t}}{C_{j,t}}\right)^{\frac{1}{\lambda_e}} + \beta\left[\eta_{t+1}\mathbb{C}_{e,t+1}^{-\mu}\left(\frac{\mathbb{C}_{e,t+1}}{E_{e,t+1}^s}\right)^{\frac{1}{\lambda_e}} E_{e,t+1}^r f'(k_{e,t}^e)\right. \\ & \left. + (1-\eta_{t+1})\mathbb{C}_{j,t+1}^{-\mu}\left(\frac{\mathbb{C}_{j,t+1}}{E_{j,t+1}^s}\right)^{\frac{1}{\lambda_e}} E_{j,t+1}^r f'(k_{u,t}^e)\right] \leq 0, \\ & I_{j,t}^e \frac{\partial L}{\partial I_{j,t}^e} = 0, \end{aligned} \tag{A.26}$$

$$\begin{aligned} [\frac{\partial L}{\partial \tilde{B}_{j,t}}]: \quad & -\mathbb{C}_{j,t}^{-\mu}\frac{\mathbb{C}_{j,t}}{C_{j,t}}^{\frac{1}{\lambda_e}} + \\ & \beta E_t \frac{R_t}{\Pi_{t+1}}\left[\eta_{t+1}\mathbb{C}_{e,t+1}^{-\mu}\left(\frac{\mathbb{C}_{e,t+1}}{C_{e,t+1}}\right)^{\frac{1}{\lambda_e}} + (1-\eta_{t+1})\mathbb{C}_{j,t+1}^{-\mu}\left(\frac{\mathbb{C}_{j,t+1}}{C_{j,t+1}}\right)^{\frac{1}{\lambda_e}}\right] \leq 0, \\ & B_{j,t}\frac{\partial L}{\partial B_{j,t}} = 0, \end{aligned} \tag{A.27}$$

$$\begin{aligned} & \lambda_{bc}(\tilde{W}_\mu + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{j,t-1} - C_{j,t} - \tilde{P}_t^e E_{j,t}^r - \tilde{B}_{j,t} - \frac{\psi_b}{2}\left[\frac{\tilde{B}_{j,t}}{\bar{\tilde{B}}} - 1\right]^2 - I_{j,t}^e) = 0, \\ & \tilde{W}_\mu + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{j,t-1} - C_{j,t} - \tilde{P}_t^e E_{j,t}^r - \tilde{B}_{j,t} - \frac{\psi_b}{2}\left[\frac{\tilde{B}_{j,t}}{\bar{\tilde{B}}} - 1\right]^2 - I_{j,t}^e \geq 0. \end{aligned}$$

We guess and verify that $\frac{\partial L}{\partial I^e_{j,t}} < 0$ and $\frac{\partial L}{\partial B_{j,t}} < 0$. It follows that unemployed workers do not invest into abatement capital $I^e_{j,t} = 0$, and do not save. We set the borrowing limit for unemployed workers to zero $\bar{b}_u = 0$, so that $\tilde{B}_{j,t-1} = 0$. The relationship between energy and non-energy consumption is as in (A.24), and the budget is exhausted.

For the capitalists, who are out of the labour force with certainty, the problem is modified to contain decision to invest into physical capital. The capitalists receive firms' dividends and return on capital.

$$L \equiv \max_{C_{c,t}, E^r_{c,t}, \tilde{B}_{c,t}, I^e_{c,t}, I_t} E_t \sum_{t=0}^{\infty} \beta^t_{c,t} U_t +$$

$$\lambda_{bc}(div_t + R_{k,t}k_{t-1} + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{c,t-1} - C_{c,t} - \tilde{P}^e_t E^r_{c,t} - \tilde{B}_{c,t}(1 + \frac{\psi_b}{2}\left[\frac{\tilde{B}_{c,t}}{\bar{\tilde{B}}} - 1\right]^2) - I^e_{c,t} - I_t), \quad (A.28)$$

with the following Kuhn-Tucker conditions:

$$[\frac{\partial L}{\partial I^e_{c,t}}] : -\lambda_{bc}\mathbb{C}^{-\mu}_{c,t}\left(\frac{1-\phi_e}{\phi_e}\right)^{\frac{1}{\lambda_e}}\left(\frac{\mathbb{C}_{c,t}}{C_{c,t}}\right)^{\frac{1}{\lambda_e}} + \beta_{c,t}\left[\mathbb{C}^{-\mu}_{c,t+1}\left(\frac{\mathbb{C}_{c,t+1}}{E^s_{c,t+1}}\right)^{\frac{1}{\lambda_e}} E^r_{c,t+1} f'(k^e_{c,t})\right] \leq 0, \quad (A.29)$$

$$I^e_{c,t}\frac{\partial L}{\partial I^e_{c,t}} = 0,$$

$$[\frac{\partial L}{\partial \tilde{B}_{c,t}}] : -\lambda_{bc}\mathbb{C}^{-\mu}_{c,t}\frac{\mathbb{C}_{c,t}}{C_{c,t}}^{\frac{1}{\lambda_e}} + \beta_{c,t}E_t\frac{R_t}{\Pi_{t+1}}\left[\mathbb{C}^{-\mu}_{c,t+1}\left(\frac{\mathbb{C}_{c,t+1}}{C_{c,t+1}}\right)^{\frac{1}{\lambda_e}}\right] \leq 0, \quad (A.30)$$

$$\tilde{B}_{c,t}\frac{\partial L}{\partial \tilde{B}_{c,t}} = 0,$$

$$[\frac{\partial L}{\partial I_t}] : \quad -\lambda_{bc}\mathbb{C}^{-\mu}_{c,t}\frac{\mathbb{C}_{c,t}}{C_{c,t}}^{\frac{1}{\lambda_e}} + \beta_{c,t}E_t\left[\mathbb{C}^{-\mu}_{c,t+1}\frac{\mathbb{C}_{c,t+1}}{C_{c,t+1}}^{\frac{1}{\lambda_e}}\left(1 - \delta + R^k_{t+1}\right)\right] \leq 0, \quad (A.31)$$

$$I_t\frac{\partial L}{\partial I_t} = 0,$$

$$\lambda_{bc}(div_t + R_{k,t}k_{t-1} + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{c,t-1} - C_{c,t} - \tilde{P}^e_t E^r_{c,t} - \tilde{B}_{c,t} - \frac{\psi_b}{2}\left[\frac{\tilde{B}_{c,t}}{\bar{\tilde{B}}} - 1\right]^2 - I^e_{c,t} - I_t) = 0,$$

$$div_t + R_{k,t}k_{t-1} + \frac{R_{t-1}}{\Pi_t}\tilde{B}_{c,t-1} - C_{c,t} - \tilde{P}^e_t E^r_{c,t} - \tilde{B}_{c,t} - \frac{\psi_b}{2}\left[\frac{\tilde{B}_{c,t}}{\bar{\tilde{B}}} - 1\right]^2 - I^e_{c,t} - I_t \geq 0.$$

For the capitalists, the solution for I_t and $I^e_{c,t}$ is given by setting (A.31) and (A.29) respectively to zero. We also show [TBA] that (A.30) holds with strict inequality and capitalists savings are zero. As long as (A.30) is strictly negative, capitalists have incentives to borrow. We limit their borrowing to $\bar{b}^c < 0$.

To solve the model, we set $f(k^e_t) = \psi_{ab}(k^e_t)^2$ for any household. The choice of the abatement function is motivated by the literature on emission abatement.

Appendix B: The Steady State Solution

We consider deterministic steady state, in which we normalize $\bar{P} = 1$ and divide all the nominal variables by $\bar{P}$. Then we can assume that the relative energy prices are unity in the steady state: $\bar{P}^e = 1$. Below all nominal variables are transformed into real, by dividing our $\bar{P} = 1$. In this section, we drop the upper bars from the steady state notation.

Firms Problem, Output and Labour Market

Given the steady state values of the share of unemployed workers, the solution for the firm's problem and the labour market allocations is straightforward. The steady state labour supply is given by:

$$\begin{aligned} N &= N(1-\omega(1-\eta)) + U\eta, \\ U &= 1 - N - \xi, \\ N &= \frac{\eta(1-\xi)}{\omega(1-\eta)+\eta}. \end{aligned} \tag{B.32}$$

Denoting steady state value of marginal product of labor $\overline{mpl} \equiv \frac{1-\gamma_k}{1-\rho_o}(K/N)^{\gamma_k}$, From (2.7) and (2.8), we express the steady state real wage:

$$\gamma \frac{1-\rho_o}{\overline{mpl}} \left(w + \kappa/\eta^{\frac{\alpha}{\alpha-1}} - \beta(1-\omega)\kappa/\eta^{\frac{\alpha}{\alpha-1}} \right) + \gamma\rho_o = \gamma - 1, \tag{B.33}$$

$$w = \left(\frac{\gamma-1}{\gamma} - \rho_o \right) \frac{\overline{mpl}}{1-\rho_o} - (1-\beta(1-\omega))\kappa/\eta^{\frac{\alpha}{\alpha-1}}. \tag{B.34}$$

Workers and Capitalist

In steady state, workers and capitalists' discount factors are equal: $\beta_c = \beta$. The steady state solution to the model becomes a function of employed and unemployed workers' abatement capital levels and their savings. These three variable can be pinned down by the following variables. We choose these particular variables as there are straightforward empirical counterparts in the Household Finance and Consumption Network (2023), and it is possible to compare our model steady state with the data on households' behaviour.

For calibrated values of $\theta^e \equiv \frac{E_e^r}{(E_e^r+C_e)} \frac{(E_{uu}^r+C_{uu})}{E_{uu}^r}$, we guess the steady state workers' savings rate and their steady state share of raw energy consumption θ_1^e. With these guessed values, we find steady state levels of abatement capital for employed and unemployed workers with $\theta_2^e \equiv \frac{E_{uu}^r}{(E_{uu}^r+C_{uu})}$:

$$k_u^e = \sqrt{1/\psi_{ab}} \left(\frac{\phi_e}{1-\phi_e} \frac{1-\theta_2^e}{\theta_2^e} \right)^{\frac{0.5}{1-\lambda_e}}, \tag{B.35}$$

$$k_e^e = \sqrt{1/\psi_{ab}} \left(\frac{\phi_e}{1-\phi_e} \frac{1-\theta_1^e}{\theta_1^e} \right)^{\frac{0.5}{1-\lambda_e}}. \tag{B.36}$$

Given, the steady state abatement capital, we solve for equilibrium interest rate R, which will determine further allocations. We find the interest rate by equalizing workers' consumption (first line) and abatement capital (second line) Euler equations:

$$\frac{1}{R} = \beta\left[\omega(1-\eta)\left(\frac{\mathbb{C}_{eu}}{\mathbb{C}_e}\right)^{-\mu}\left(\frac{\mathbb{C}_{eu}/E^s_{eu}E^s_{eu}/C_{eu}}{\mathbb{C}_e/E^s_eE^s_e/C_e}\right)^{\frac{1}{\lambda_e}}+(1-\omega(1-\eta))\right], \tag{B.37}$$

$$\begin{aligned}&\left(\frac{1-\phi_e}{\phi_e}\right)^{\frac{1}{\lambda_e}}\left(\frac{E^s_e}{C_e}\right)^{\frac{1}{\lambda_e}}\frac{1}{f'(k^e_e)E^r_e} = \\ &\beta\left[(1-\omega(1-\eta))+\omega(1-\eta)\left(\frac{\mathbb{C}_{eu}}{\mathbb{C}_e}\right)^{-\mu}\left(\frac{\mathbb{C}_{eu}}{E^s_{eu}}\frac{E^s_e}{\mathbb{C}_e}\right)^{\frac{1}{\lambda_e}}\frac{E^r_{eu}f'(k^e_u)}{E^r_ef'(k^e_e)}\right]\end{aligned} \tag{B.38}$$

Denote $A = \left(\frac{\mathbb{C}_{eu}}{\mathbb{C}_e}\right)^{-\mu}\left(\frac{\mathbb{C}_{eu}/E^s_{eu}}{\mathbb{C}_e/E^s_e}\right)^{\frac{1}{\lambda_e}}$. We express A from Euler equations and equalize both equations.

$$\left[\frac{f(k^e_e)}{f'(k^e_e)E^r_e}\frac{1}{\beta}-(1-\omega(1-\eta))\right]\frac{1}{\omega(1-\eta)}\frac{E^r_ef'(k^e_e)}{E^r_{eu}f'(k^e_u)} = A,$$

$$\left[\frac{1}{R\beta}-(1-\omega(1-\eta))\right]\frac{1}{\omega(1-\eta)}\frac{f(k^e_e)}{f(k^e_u)} = A,$$

$$R = \left(\left[\frac{f(k^e_e)}{f'(k^e_e)E^r_e}\frac{1}{\beta}-(1-\omega(1-\eta))\right]\frac{E^r_ef'(k^e_e)/f(k^e_e)}{E^r_{eu}f'(k^e_u)/f(k^e_u)}+(1-\omega(1-\eta))\right)^{-1}\frac{1}{\beta}. \tag{B.39}$$

Given R and steady state workers propensity to save, we find the employed workers saving decisions and averaged bond holdings among the employed workers:

$$\tilde{B}_e = \tilde{W}\frac{1-\tau}{\omega(1-\eta)+1/cmrs}, \tag{B.40}$$

$$\tilde{B}'_e = (1-\omega(1-\eta))\tilde{B}_e. \tag{B.41}$$

In the steady state, capitalists' borrowing limit is equal to workers' savings:

$$\bar{b}^c = -\frac{\tilde{B}_eN}{\xi}. \tag{B.42}$$

With the capitalists borrowing limit and equilibrium interest rate, we can solve for capitalists' consumption and abatement investment by solving the following system. The first equation is the steady state version of abatement capital Euler equation, from which we have expressed capitalists' raw energy consumption. The second - is the steady state relationship between energy and non-energy consumption as in (A.24), the last equation is capitalists' budget constraint.

$$E^r_c = 0.5\frac{K^e_c}{\beta}, \tag{B.43}$$

$$C_c = \frac{1-\phi_e}{\beta\phi_eK^e_c}\left(\psi_{ab}(K^e_c)^2\right)^{2-\lambda_e}, \tag{B.44}$$

$$\delta_eK^e_c+E^r_c+C_c-((1-\tau)(div-I)/ksi+b^c(R-1)) = 0. \tag{B.45}$$

We further express the energy and non-energy consumption for every agent as a function of their abatement capital. To verify the initial guess, we utilize the remaining unused equations - resource constraint (2.14) and employed workers' abatement capital Euler equation (A.20). We compare the resulting steady state ratios with those from the data as reported in Table 2.

Appendix C: Calibrated Parameters: Standard Values

Table 3: Calibrated Parameters: Standard Households' and Real Sector

Name	Symbol	Value
Share of capital in production function	γ_k	0.3
Capital depreciation	δ_k	0.025
Elasticity of subst. goods varieties	γ	7
Household's discount factor	β	0.98
Household' risk aversion	μ	2
Labour market:		
Matching function elasticity	α	0.5
Separation rate	ω	0.02
Vacancy costs	κ	$0.1\bar{w}$
Real wage persistence	γ_w	0.1
Real wage flexibility	ξ	0.0001
Monetary policy parameters:		
Monetary policy persistence	ρ_r	0.93
Other variables:		
Price duration		6 months

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