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Monetary Policy and Energy Price Shocks

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Abstract

A New Keynesian framework with endogenous energy production is proposed to investigate the role of monetary policy in addressing disturbances in energy markets. The novelty of the model lies in the endogenous production of energy with convex costs, explicit modeling of goods with different degrees of energy-dependency and sectoral price rigidities. Our analyses prescribe the desirable monetary responses to four types of energy price shocks, highlighting the distinct characteristics of each shock and affirming the need for diverse policy considerations. We also found several points of divergence in relation to previous studies on addressing energy supply shocks. In addition, we shed light on the role of sectoral price rigidities in the shocks' propagation.

JEL classifications: C68, E32, E52, Q43

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1 Introduction

Research on the effect of oil price shocks on the economy has been extensive, as shown in both the empirical and theoretical sides of the literature. A large body of this literature focuses on the role of monetary policy in times of such shocks, first on whether and how much monetary policy exacerbates the negative effects of an oil price increase, and second on the prescriptions for an optimal policy reaction. On this latter question, results from a number of theoretical investigations involving New Keynesian DSGE models have produced diverse answers. For instance, Leduc and Sill (2004) prescribe price stability as the policy of choice in addresing energy (oil) supply shocks, whereas Bodenstein et al. (2008) argue against this policy, opting instead for more output stabilization. More recently, there is a growing justification to go beyond oil supply shocks toward examining the possible different sources of energy price increases. As Kilian (2009) noted, it is of crucial and practical importance to disentangle the different typess of supply and demand shocks that could affect energy markets and to distinguish their effects because not all energy price increases have the same underlying cause or should be treated equally (also see, e.g., Kilian and Murphy 2012, 2013; Baumeister and Peersman 2013).

The aim of this paper is to address the lack of consensus concerning the case of an energy supply shock and the question of how monetary policy should respond to a wider set of energy price increases. It joins the literature on monetary policy in the context of energy/oil supply shocks, to which the works of Bernanke, Gertler and Watson (1997), Hamilton and Herrera (2004), Leduc and Sill (2004) and Kormilitsina (2011) have made major contributions. The paper brings together diverse conclusions on optimal monetary conduct in response to oil/energy supply shocks and examines where our results place us along this inflation-output divide. Second, we use the framework to extend the question of desirable monetary responses to other types of shocks to energy markets. The endogenous energy production feature brings completion to a theoretical model with energy at its core and allows energy production and energy price to respond fully to economic conditions. The introduction of convex costs of energy production helps create more-realistic dynamics of energy price and energy supply in response to demand shocks to the energy market. The third contribution by this paper lies in the multi-sector feature of the theoretical setup. In introducing sectoral price stickiness, allied with goods with different degrees of energy dependence (in terms of their consumption), we set out to investigate whether the relative price rigidity between the two sectors plays an important role in determining the response of the economy to energy price shocks and to monetary policy reactions.

We make use of the RBC model in Huynh (2015), which comprises a fully endogenous energy sector with convex costs in production, a durable sector and a non-durable sector. New Keynesian features are introduced in the form of monopolistic competition and price rigidity for the durable and non-durable sectors (energy price is assumed to be flexible), distortionary taxes and fiscal and monetary authorities. Sectoral price rigidity follows Monacelli (2009), but our framework is novel in both its setup and approach because it is augmented by the incorporation of energy production and consumption, and it is used for analysing energy-related issues. In the strand of related theoretical models, the works of Leduc and Sill (2004), Kormilitsina (2011), Bodenstein et al. (2008) and Nakov and Pescatori (2010) provide the background and motivation for our analysis. However, our framework departs from previous efforts in a number of important dimensions. Leduc and Sill (2004), Kormilitsina (2011) and Nakov and Pescatori (2010) do not have oil/energy consumption in the household, thereby missing out on an important channel in terms of the direct income effect through which energy affects the demand side of the economy. Both Leduc and Sill (2004) and Kormilitsina (2011) also assumed an exogenous oil price process. In this type of setup, all instances of energy-related shocks are represented by an exogenous energy price increase and are therefore considered the same in terms of their effects on the economy. In such a setup, it is therefore not possible to go beyond the case of energy supply shock. Bodenstein et al. (2008) and Nakov and Pescatori (2010) incorporated features of endogenous energy production, but in Bodenstein et al. (2008), there was no actual energy (oil) production, and Nakov and Pescatori (2010) employed a different structure of organization of the oil industry. Thus, in Bodenstein et al. (2008), whereas energy price can be considered endogenous, energy supply is not and represents the extreme case of a perfectly inelastic energy source. Energy supply in Nakov and Pescatori (2010), although endogenous, has too-high price elasticity in the short run. Our setup is therefore strongly distinguished by the feature of convex costs for the energy producer. This feature ensures a highly inelastic energy supply to changes in energy price, as empirically observed[1], and endogenously creates energy price dynamics that come close to the data[2].

In terms of examining monetary responses for different types of energy price shocks, Bodenstein et al. (2012) provided an investigation into this issue. However, in Bodenstein et al. (2012), the oil supply is again an exogenous endowment, which represents the extreme case of a perfectly inelastic oil supply and does not capture the dynamics of energy production. In addition, their analysis had a different focus. They illustrated the different natures of energy price shocks through the estimated monetary responses that they induce, not in terms of optimal monetary policy. Their analysis of optimal policy responses was also different because the search was for a class of optimal monetary rules in the presence of all shocks, and comparisons were made with actual estimated rules. In our paper, in contrast, we focus individually on each type of energy price shocks and investigate the monetary policy rule that maximizes the response of welfare under each shock. We thus shed light on the different nature of each shock through the optimal monetary response that is needed. We also consolidate the number of energy price shocks to three classes of shocks, in contrast to 15 different shocks in Bodenstein et al. (2012), to make the analysis more in line with Kilian (2008, 2009).

In the context of monetary analysis, our model also differs from these aforementioned frameworks by explicitly modeling the consumption and production of goods with different degrees of energy-dependence[3]. This setup introduces additional dynamics into

[1]Krichene (2005) gave a range of estimates for the short-run price elasticity of oil supply and natural gas supply and found them to be highly inelastic, with the highest estimate not exceeding 0.1.

[2]Kim and Loungani (1992) calculated the relative volatility of energy price to output at 6.02 using US annual data from 1949 to 1987. Huynh (2015), with convex costs in energy production calibrated to give a price elasticity of energy supply at around 0.1, returns this ratio at 7.1.

[3]Dhawan and Jeske (2008) employed consumptions of durables and non-durables but not in a monetary policy context.

household consumption behaviors in response to energy price increases and creates heterogeneity in how these shocks affect the different goods sectors. The shocks studied in this paper follow those of Kilian (2008, 2009): productivity shock to the energy sector, representing the usual energy supply shock; TFP shock to the non-energy sectors, which is a type of aggregate shock to energy demand; and two energy market-specific demand shocks coming from the household and the producers, respectively. We confine the shocks to those originating from within the economy to facilitate comparisons with Leduc and Sill (2004) and Kormilitsina (2011) and to focus solely on the monetary policy aspect by abstracting from the international channels of transmission of energy price shocks.

Concerning the energy supply shock, our results differ from the above-mentioned in several aspects and find agreement in others. We did not find that price stability is the best, in contrast to Leduc and Sill (2004). Our findings are more in line with Bodenstein et al. (2008), in that we lean toward output stabilization with a balanced, dual-mandate policy to minimize welfare losses in response to this shock. The conclusions drawn by Nakov and Pescatori (2010) also differ from ours. Although they did propose a certain degree of focus on output stabilization as an optimal form of monetary policy, their favorable view of strict price stability and aggressive inflation-fighting policies are in contrast to what we obtained from our analyses.

Extending the analysis to other types of energy price shocks, we found that in the event of a positive TFP shock to non-energy producers, which increases the overall demand for energy, a strong focus on inflation is best in terms of ensuring the highest welfare gain. We showed that this instance of energy price shock is very distinct from the energy supply shock, not only in terms of the responses of the economy but also in terms of the relative performance of alternative monetary regimes. The two specific demand shocks to the energy market, however, require actions qualitatively similar to the case of an energy supply shock. Even so, the effectiveness of the best performing policy varies between these two shocks due to the distinct nature and effect of each shock, particularly on the durable sector[4].

[4]Huynh (2015).

Additionally, we showed that the price rigidity of the more energy-consuming goods plays a greater role in the propagation of energy price shocks. Output, consumption and other macro variables show higher sensitivity to variation in the price stickiness of durable goods. Durables' price rigidity also influences the non-durable sector's behavior more than vice versa. This pattern is a result of the more energy-dependent goods sector always showing more volatile responses when energy price changes and of the interplay between the substitution effect and the income effect that causes the consumption of durables to vary little when the price of non-durables changes.

2 Model Description

2.1 Households

The representative household consumes a CES aggregation of durables and non-durables of the following form

$$c_t = [\alpha^{1-\rho}(u_t d_t)^\rho + (1-\alpha)^{1-\rho} {n_t}^\rho]^{1/\rho}$$

where n_t is the household's consumption on non-durables, d_t is the household's stock of durables and u_t is the utilization rate of this durables stock. The elasticity of substitution between durables and non-durables is represented by $\frac{1}{1-\rho}$. Together, $u_t d_t$ defines the service the household derives from its existing stock of durables in period t.

Household energy usage

Household use of durables needs energy, the amount of which ($e_{h,t}$) is variable in each period and directly dependent upon the utilization rate and stock of durables. Energy consumption does not enter the utility function directly; instead, its cost enters into the household budget constraint. In this specification, the model makes use of the specification in Finn (2000) and extends it to the household. Household use of energy in each period can be considered a function of the stock of durables multiplied by its utilization rate $e_{h,t} = f(u_t d_t)$. In all analyses performed in this paper, the amount of energy needed to sustain a utilization rate u_t of a stock of durables d_t is assumed linearly dependent upon their product $u_t d_t$, that is, $e_{h,t} = a u_t d_t$, where a is a constant to be calibrated. This linear relationship carries the assumption that aggregate durables have a constant energy intensity.

In addition, to model an energy market-specific demand shock originating from the household, we add the following exogenous shock to the household energy demand function:

$$e_{h,t} = \mu_{a,t} a u_t d_t \tag{1}$$

where $\mu_{a,t}$ is an AR(1) process with mean 1 and subject to i.i.d. innovations:

$$\mu_{a,t} - 1 = \rho_a(\mu_{a,t-1} - 1) + \epsilon_{a,t}, \epsilon_{a,t} \sim^{i.i.d} N(0, \sigma_{e,a}^2) \tag{2}$$

The representative household problem is therefore to maximize its expected lifetime utility:

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_t, h_t) \tag{3}$$

where

$$U_t = \varphi log c_t + (1 - \varphi) log(1 - h_t)$$

subject to the following budget constraint:

$$\begin{aligned} &(1 + \tau_{e,c,t}) p_{e,t} a u_t d_t + (1 + \tau_{c,t}) p_{n,t} n_t + (1 + \tau_{c,t}) p_{d,t} i_{d,t} + p_{d,t} i_{k,t} + i_{B,t} \\ &= (1 - \tau_{i,t})(w_t h_t + r_t k_t) + R_t B_t \end{aligned} \tag{4}$$

where $i_{d,t}$, $i_{k,t}$ and $i_{B,t}$ denote investments in durables, capital and government risk-free bonds respectively, r_t the return on capital, w_t the wage and R_t the return on government bonds. The household earns its income from the rental of its capital stock to firms, its labor service and the return on its government bonds. The taxes it must pay are an ad-valorem tax on its energy consumption, income tax on its wage and return on capital, and consumption tax on its durable and non-durable consumption. Investments in capital and durables are subject to the following adjustment costs:

$$i_{d,t} = d_{t+1} - (1-\delta_{d,t})d_t + \frac{\omega_{d1}}{1+\omega_{d2}}\left(\frac{d_{t+1}-d_t}{d_t}\right)^{1+\omega_{d2}} \tag{5}$$

$$i_{k,t} = k_{t+1} - (1-\delta_k)k_t + \frac{\omega_{k1}}{1+\omega_{k2}}\left(\frac{k_{t+1}-k_t}{k_t}\right)^{1+\omega_{k2}} \tag{6}$$

Investment in government bonds is also subject to a portfolio adjustment cost and is given by

$$i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B1}}{1+\omega_{B2}}\left(B_{t+1}-\bar{B}\right)^{1+\omega_{B2}} \tag{7}$$

With $\bar{B}$ calibrated, it is then possible to solve for the aggregate price level in the economy. The rate of depreciation of durables is variable and varies positively with the utilization rate. Here, we use a power-function form for the depreciation rate, following Finn (2000)

$$\delta_{d,t} = \frac{a_1}{a_2+1}{u_t}^{a_2+1} \tag{8}$$

The household's choice of $\{n_t, u_t, h_t, d_{t+1}, k_{t+1}, B_{t+1}\}$ to maximize (1) subject to (2), (3), (4), (5) and (6) results in the usual first-order conditions, detailed in appendix A.

2.2 Energy Usage in Production

This framework assumes that each sector's energy use is tied directly to its use of capital, i.e., $e_{f,t} = g(k_t)$, with g a function to be determined. Similar to the household case, g is calibrated to be a simple linear function, except for the energy sector; that is, a non-energy sector's energy consumption is given by $e_{f,t} = bk_t$, where b is a constant. For the overall analysis in this paper, it suffices to assume that b is the same for the two non-energy sectors. This parameter b is thus a technological parameter that embodies the energy intensity of capital. The relationship $e_{f,t} = bk_t$ implies a very high degree of complementarity between capital and energy. With this specification, we emphasize the fundamental importance of energy in production.

Again, we can model an energy market-specific demand shock originating from the producers by introducing an exogenous shock to the producers' energy demand function such that for each producer

$$e_{j,t} = \mu_{b,t} b k_{j,t} \tag{9}$$

where $\mu_{b,t}$ is an AR(1) process with mean 1 and subject to i.i.d. innovations:

$$\mu_{b,t} - 1 = \rho_b(\mu_{b,t-1} - 1) + \epsilon_{b,t}, \epsilon_{b,t} \sim^{i.i.d} N(0, \sigma^2_{e,b}) \tag{10}$$

2.3 Energy Production

The energy sector operates in a perfectly competitive market, and energy price is assumed fully flexible. The model implements an energy production with convex costs to bring about low price elasticity of energy supply.

The production function of the energy sector takes the form

$$y_{e,t} = exp(A_{e,t}) k^{\gamma_e}_{e,t} h^{1-\gamma_e}_{e,t} \tag{11}$$

$A_{e,t}$ is the energy sector-specific productivity process:

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_{e,t} \tag{12}$$

Energy needed to operate capital in energy production is dependent upon the level of output at an increasing rate:

$$b_{e,t} = \frac{\omega_{e1}}{(1 + \omega_{e2})} (k^{\gamma_e}_{e,t} h^{1-\gamma_e}_{e,t})^{1+\omega_{e2}} \tag{13}$$

This convex energy intensity of capital used in energy production creates a mechanism whereby when a demand shock hits the energy market the energy sector cannot simply expand its output by a large percentage quickly. The calibration section will explain in more detail the process of calibrating this convex cost.

The firm's maximization is

$$\max_{\{p_{e,t},k_{e,t},h_{e,t}\}} \{p_{e,t}y_{e,t} - w_t h_{e,t} - r_t k_{e,t} - (1+\tau_{e,f,t})p_{e,t}b_{e,t}k_{e,t}\} \tag{14}$$

where $\tau_{e,f,t}$ is an ad-valorem tax on the firm's energy usage.

2.4 Durable and Non-durable Final Goods Producers

Each sector has a perfectly competitive final good producer that purchases the intermediate goods in that sector and assembles them into the final product according to the following production function:

$$y_{i,t} = \left(\int_0^1 y_{i,j,t}{}^{\frac{\epsilon_i - 1}{\epsilon_i}} dj \right)^{\frac{\epsilon_i}{\epsilon_i - 1}} \tag{15}$$

where ϵ_i is the elasticity of substitution between the differentiated varieties in sector i $(i = d, n)$, $y_{i,j,t}$ the output of each firm j in sector i, and $y_{i,t}$ the output of the final goods producer in sector i.

Profit maximization means that each firm j in sector i faces the following demand schedule for its good:

$$y_{i,j,t} = \left(\frac{p_{i,j,t}}{p_{i,t}} \right)^{-\epsilon_i} y_{i,t} \tag{16}$$

where $p_{i,j,t}$ is the price of firm j's good in sector i, and $p_{i,t}$ the aggregate price index in sector i, given by

$$p_{i,t} = \left(\int_0^1 p_{i,j,t}{}^{1-\epsilon_i} dj \right)^{\frac{1}{1-\epsilon_i}} \tag{17}$$

2.5 Durable and Non-durable Intermediate Goods Producers

It is assumed that in each sector i, there exists a continuum (with a mass index of 1) of firms, each producing a variety j of that sector's goods in a monopolistically competitive market. Each firm j in each sector has access to the same kind of production technology specific to that sector:

$$y_{i,j,t} = exp(A_t)\,(k_{i,j,t})^{\gamma_i}\,(h_{i,j,t})^{1-\gamma_i} - \chi_i \tag{18}$$

where $i = d, n$ and χ_i denotes fixed costs of production for sector i.

A_t is a technology process that is common across the two sectors:

$$A_t = \rho_A A_{t-1} + \epsilon_{A,t} \tag{19}$$

Since each firm has monopolistic power over its own variety, it can set prices to maximize its profit. However, every time it does so, it incurs a Rotemberg-style quadratic cost proportional to final output in the following form:

$$\frac{\vartheta_i}{2}\left(\frac{p_{i,j,t}}{p_{i,j,t-1}} - 1\right)^2 y_{i,t} \tag{20}$$

Each firm's objective is to choose a sequence of price, labor and capital $\{p_{i,j,t}, h_{i,j,t}, k_{i,j,t}\}$ to maximize its expected discounted nominal profits:

$$E_0\{\sum_{t=0}^{\infty} \Lambda_{i,t}(p_{i,j,t}y_{i,j,t} - w_t h_{i,j,t} - (r_t + bp_{e,t}(1+\tau_{e,f,t}))k_{i,j,t} - \frac{\vartheta_i}{2}\left(\frac{p_{i,j,t}}{p_{i,j,t-1}} - 1\right)^2 p_{i,t}y_{i,t})\} \tag{21}$$

where $\Lambda_{i,t}$ is the stochastic discount factor.

By log-linearizing the resulting first-order condition of the above problem around a zero-inflation deterministic steady state, a sectoral Phillips curve is obtained for each sector i:

$$\hat{\pi}_{i,t} = \beta E_t[\hat{\pi}_{i,t+1}] + \frac{\epsilon_i - 1}{\vartheta_i}\hat{mc}_{i,t} \tag{22}$$

where $\hat{\pi}_{i,t}$ denotes the log-deviation of sector i's inflation from its steady-state value, and $\hat{mc}_{i,t}$ the log-deviation of sector i's real marginal cost from the steady state.

In a symmetric equilibrium, each sector i's real marginal cost is given by

$$mc_{i,t}exp(A_t)(1-\gamma_i)\left(\frac{k_{i,t}}{h_{i,t}}\right)^{\gamma_i} = \frac{w_t}{p_{i,t}} \tag{23}$$

together with sector i's first-order condition resulting from cost minimization:

$$\frac{1-\gamma_i}{\gamma_i}\frac{k_{i,t}}{h_{i,t}} = \frac{w_t}{r_t + bp_{e,t}(1+\tau_{e,f,t})} \tag{24}$$

Wage and the rate of return on capital are assumed equalized across all three sectors.

2.6 CPI Inflation

The CPI index for the economy is given by

$$p_t = \left[\alpha\left(p_{d,t} + ap_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha)p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}} \tag{25}$$

Gross CPI inflation is thus

$$\pi_t = \frac{p_t}{p_{t-1}} \tag{26}$$

2.7 Fiscal and Monetary Policies

On the fiscal side, the government levies three types of taxes: ad-valorem tax on energy consumption on both the household and the producers, consumption tax on durable and non-durable consumption, and income tax on return on capital and wage. In addition, it also issues risk-free bonds each period to the household. This revenue from taxes and bonds is used to finance its spending and interest payment on the household's current bond holdings.

Its budget constraint is given by

$$\tau_{e,c,t}p_{e,t}au_td_t + \tau_{e,f,t}p_{e,t}(b(k_{d,t}+k_{n,t}) + b_{e,t}k_{e,t}) + \tau_{c,t}(p_{n,t}n_t + p_{d,t}i_{d,t}) + \tau_{i,t}(r_tk_t + w_th_t)$$
$$+ i_{B,t} = p_tg_ty_t + R_tB_t \tag{27}$$

where g_t indicates government spending as a fraction of real output and is given as an exogenous stochastic process. Here, we assume that for its spending, the government consumes a CES basket of durables and non-durables, similarly to the household, *sans* the utilization rate for durables:

$$g_t y_t = \left[\alpha^{1-\rho} g_{d,t}^{\rho} + (1-\alpha)^{1-\rho} g_{n,t}^{\rho}\right]^{1/\rho} \tag{28}$$

such that

$$p_t g_t y_t = p_{d,t} g_{d,t} + p_{n,t} g_{n,t} + p_{e,t} a g_{d,t} \tag{29}$$

The fiscal authority follows a passive fiscal regime, with the sole aim of debt stabilization. To do so, it sets tax rates for each period as a function of the outstanding bond balance at the beginning of the period[5]:

$$log\left(\frac{\tau_{(),t}}{\bar{\tau}_{()}}\right) = \rho_{()} log\left(\frac{\tau_{(),t-1}}{\bar{\tau}_{()}}\right) + \phi_{()} log\left(\frac{B_t}{\bar{B}}\right) \tag{30}$$

where $\tau_{(),t}$ represents the general term for all four types of taxes in our model, with $() = (e,t), (e,f), c, i$, and $\bar{\tau}_{()}$ the corresponding steady-state rate for each tax. $\bar{B}$ is the steady-state value of nominal government debt.

The monetary authority sets the short-term nominal interest rate on risk-free bonds according to the following Taylor-type rule:

$$R_t - R^* = \alpha_R (R_{t-1} - R^*) + \alpha_\pi (\pi_t - \pi^*) + \alpha_y (y_t - y_{t-1}) + \epsilon_{r,t} \tag{31}$$

where R^* is the interest rate target consistent with the steady-state nominal return on risk-free bonds, π^* is the inflation target, and $\epsilon_{r,t}$ is an exogenous shock to the interest rate rule.

2.8 Aggregation and Equilibrium

Factor markets clear

$$k_t = k_{d,t} + k_{n,t} + k_{e,t} \tag{32}$$

[5]These rules follow closely in form those of Forni, Monteforte and Sessa (2009).

$$h_t = h_{d,t} + h_{n,t} + h_{e,t} \tag{33}$$

as do goods markets

$$y_{d,t} = i_{d,t} + i_{k,t} + g_{d,t} + \frac{\vartheta_d}{2}(\pi_{d,t} - 1)^2 y_{d,t} \tag{34}$$

$$y_{n,t} = n_t + g_{n,t} + \frac{\vartheta_n}{2}(\pi_{n,t} - 1)^2 y_{n,t} \tag{35}$$

Aggregate output (value added) is defined as

$$p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t \tag{36}$$

2.9 Exogenous driving processes

The model is driven by four main shocks: the conventional TFP shock that is common to both the durable and non-durable sectors, a productivity shock that affects the energy sector alone, and shocks to the energy intensities of durables and of capital (shocks to a and to b, respectively).

3 Model Calibration, Solution and Welfare Measure

3.1 Model Calibration

The model is calibrated to the broad characteristics of the U.S. economy at quarterly frequency. Table 6 displays the empirical ratios of main U.S. macro variables obtained from Dhawan and Jeske (2008)[6] for the calibration of the model.

Certain standard parameters are calibrated following the standard literature. The discount factor β is set at 0.99, which translates to an annual interest rate of approximately 4%. The share of consumption in the household utility function φ is set at 0.34, and the share of durables α in consumption is set at 0.2. Empirical research sets the elasticity of substitution between durables and non-durables close to 1. Here, it is set at 0.99 for the main analyses, and the CES parameter of the household utility

[6] Dhawan and Jeske (2008), Table 1.

function is therefore $\rho = 1 - 1/0.99$, which is negative and indicates that durables and non-durables are somewhat complementary. Other parameters are calibrated to produce theoretical moments of model aggregates that reproduce as best as possible the empirical moments found in aggregate US data. Quarterly capital depreciation is calibrated at 1.5%, whereas the parameters of the durable depreciation function are chosen to produce a steady-state quarterly depreciation rate of 3.3% and a utilization rate of approximately 80% for durables. Hence, $a_1 = 0.055$, and $a_2 = 0.3$. The calibration of the parameters a and b, the degrees of energy-dependence of durables and capital respectively, is based approximately on the empirical ratios E_h/Y and E_f/Y in Table 6. The resulting calibration is $a = 0.06$, and $b = 0.012$. The functional forms of capital and durable adjustment costs are given in the form of a general power function governed by two parameters ω_1 and ω_2. In this paper, we assume a quadratic form for both stocks; thus, $\omega_{d2} = \omega_{k2} = 1$. The remaining choice of ω_1 does not affect the steady state of the model; thus, it is chosen using the volatilities of capital and durables in the data as a guide. We used the following calibration: $\omega_{k1} = 3, \omega_{k2} = 1, \omega_{d1} = 6$, and $\omega_{d2} = 1$.

The parameters of the three sectors' production functions are also calibrated using the ratios in Table 6 as a guide plus additional ratios such as the ratio of durable consumption to total real personal consumption. The capital share of the energy sector is also calibrated to be greater than the average value of 0.36 usually found in the literature, meaning that the energy sector is more capital-intensive. Additionally, the calibration of these parameters depends largely upon the equilibrium dynamics of the system, meaning that they are also carefully chosen so that the model produces a stable equilibrium.

The parameters for the convex cost function of the energy sector are calibrated to bring about low price elasticity of energy supply and energy price dynamics that reflect empirical facts. In addition, their choices are also constrained by the volatility of various energy-related variables such as household and producer energy consumption and energy output and, of no less importance, by the equilibrium dynamics of the model. Parameter values that yield very low price elasticity of energy supply result in excess volatility of variables and often cause the model to have no stable equilibrium. Here, we chose a cubic power function form for the convex cost, so that $\omega_{e2} = 2$. ω_{e1} is then calibrated to be 3.77 to yield a price elasticity of energy supply of approximately 0.1, keeping it as close to the range of empirical estimates as possible while ensuring that the model has a stable equilibrium around the steady state.

Both the durable and non-durable sectors have their elasticity of substitution between their own varieties, ϵ_d and ϵ_n, set at 5, a value frequently used in the literature, to yield a steady-state flexible-price markup of 25%. The price adjustment cost parameters for the durable and non-durable sectors, ϑ_d and ϑ_n , are calibrated following the method used in Monacelli (2009), which matches the coefficient on the deviation of real marginal cost in the new Keynesian Phillips curve obtained in this model with its counterpart in the Phillips curve obtained from Calvo-type price rigidity. In the usual framework of price rigidity using Calvo-style contracts, the fraction of firms that cannot change their prices in any given quarter is set at 0.75 to obtain a price contract length of approximately 4 quarters, a standard calibration in the recent literature. The coefficient on the deviation of real marginal cost in such Phillips curve is given by $\frac{(1-\theta)(1-\theta\beta)}{\theta}$ with $\theta = 0.75$, whereas that in the Phillips curve derived here is $\frac{\epsilon_i - 1}{\vartheta_i}$. Equating these two thus yields $\vartheta_d = \vartheta_n = 46$, meaning that for the baseline analysis, the prices of the two sectors are considered equally sticky.

Ad-valorem energy taxes are calibrated to be 10% at the steady state, whereas income tax is 15%, and consumption tax is 7%. Government spending is calibrated to be 18% of output at the steady state. For the baseline Taylor-type monetary policy rule, we follow the estimates of Clarida, Gali, and Gertler (2000), which were also used in Leduc and Sill (2004), setting $\alpha_R = 0.8$, $\alpha_\pi = 0.2$, and $\alpha_y = 0.09$. The parameters for the tax rules are calibrated to ensure a determinate equilibrium for the model and stable dynamics of government debt. They are chosen to be $\rho_{e,c} = \rho_{e,f} = \rho_c = \rho_i = 0.8$, and $\phi_{e,c} = \phi_{e,f} = \phi_c = \phi_i = 0.12$.

3.2 Model Solution and Welfare Measure

The model is solved for its steady state using a non-linear solver, and the set of equilibrium conditions is approximated around the steady state using the first-order perturbation method. The system's decision rules and transition functions are thus obtained.

The welfare variable is defined in the model as a value function of the following form:

$$V_t = U_t(c_t^*, h_t^*) + \beta V_{t+1} \tag{37}$$

where $U_t(c_t^*, h_t^*) = \phi log c_t^* + (1-\phi)log(1-h_t^*)$ denotes the optimized instantaneous utility derived from the optimal decisions of c_t and h_t. This welfare variable can then be solved together with the model's equilibrium conditions, and the resulting law of motion for V_t yields the stream of maximized welfare for the household.

With this welfare variable, we can obtain an impulse response of social welfare to each energy price shock, allowing us to compute a measure of welfare loss for the shock under analysis, calculated as the accumulated deviation of V_t from the steady-state welfare over the time horizon of the deviation. This welfare loss allows us to rank different monetary policy regimes in response to energy price shocks in terms of how much welfare is lost (or gained) under each regime.

4 Cyclical Properties

The model is calibrated with shocks to the productivity processes of the non-energy sectors and the energy sector. The standard errors of the two shocks are chosen to produce moments that are closest to those found in U.S. data. Table 1 compares the relative volatility of various aggregates to output between the model and U.S. data. The empirical ratios were calculated from Dhawan and Jeske (2008), which was also used initially for reference and calibration.

Variables	Model	U.S. data
Output	1	1
Consumption	0.67	0.80
Nondurables consumption	0.59	0.52
Durables consumption	2.91	2.90
Capital Investment	3.18	3.42
Hours	0.62	0.96
Household's energy consumption	1.73	1.34

Table 1: Relative volatility of aggregates to output

These relative volatilities illustrate the cyclical properties of the model, which broadly reflect the cyclical patterns of the U.S. economy. Total consumption and consumption of non-durables are both less volatile than is output, and althought total consumption is less volatile in the model than in the data, consumption of nondurables is less volatile than is total consumption and reflects the trend in the data. Investments in the model are both significantly more volatile than output, which is also the case empirically. Furthermore, consumption of durables comes close to matching its empirical counterpart, as does capital investment.

Household energy consumption, however, has a higher volatility in the model than in the data. The model also does less well in reflecting hours worked because the relative volatility of hours worked in the model is lower. A possible source of this low volatility concerns the frictionless movement of labor among the three sectors in the model. By making the relocation of labor more difficult/costly, labor movements might be made more realistic, which might help increase the volatility of total labor.

The presence of an energy sector produces an endogenous energy price, and the model produces energy price dynamics that come quite close to that found in the data. Table 2 shows the relative volatility of energy price to output and energy price-output correlation. For comparison, we present the same quantities calculated from Kim and Loungani (1992) in column 3. From the data, it is found that energy price is highly volatile, its percent standard deviation is several times that of output, and its correlation with output is negative. We can see that the model captures these features of energy price dynamics reasonably well. Kim and Loungani (1992) calculated the ratio of percent standard deviation of energy price to that of output to be 6, and their correlation to be -0.44 using annual data. Our model puts these two quantities at 6.22 and -0.42, respectively, calibrated at quarterly frequency.

	Model	**Kim and Loungani (1992)**
Energy price-output	6.22	6.02
Energy Price-Output Corr	-0.42	-0.44

Table 2: Energy Price Dynamics. Row 1 shows the relative standard deviation of energy price to output, row 2 displays the correlation between energy price and output.

5 Systematic Monetary Policy Response to Energy Price Shocks

5.1 Energy Supply Shock

One of the main areas of debate has been the role of monetary policy in the event of an adverse energy supply shock. Kormilitsina (2011) and Leduc and Sill (2004) arrived at different conclusions on what the optimal monetary policy would be. Bodenstein et al. (2008) and Nakov and Pescatori (2010) incorporated features of endogenous energy price into their frameworks and also arrived at different optimal monetary policy responses to an energy supply shock. We conducted our own analysis of this shock using our framework to see where our results sit in relation to these previous works and to shed light on the differences between our findings and their results. We calibrated the shock to the productivity of the energy sector to produce a 10% increase in energy price. This is a temporary shock that creates a half-life for the energy price increase of approximately 12 quarters. For our analysis, the inflation coefficient (α_π) of the Taylor rule is swept from 0 to 0.4, and the output coefficient (α_y) is swept from 0 to 0.3. Figure 1 shows the welfare loss corresponding to each combination of (α_π, α_y), whereas Table 3 compares the welfare losses of selected regimes: price-stability, output-stability, interest-peg and the best-performing regime.

Regimes	**Welfare Gain (%)**
Max price-stability	-8.32
Max output-stability	-7.62
Interest-peg	-7.72
Best-performing ($\alpha_\pi = 0.24$, $\alpha_y = 0.3$)	-6.74

Table 3: Performance of various monetary regimes.

One main observation stands out when the monetary policy function pays no attention to output. As more emphasis is placed on fighting inflation, welfare loss becomes progressively worse and then recovers, although the objective of obtaining a smoother response in inflation is achieved. When more weight is placed on output, welfare loss becomes smaller, but inflation also rises. However, at the highest value of the output coefficient (0.3), as the inflation coefficient increases, inflation response also becomes smoother (Fig. 2). A larger weight on inflation helps manage inflation expectations and thus keeps the interest rate from changing too rapidly from one period to the next. Responding to output alone doesn't appear to bring much change in welfare loss (the outer edge of the surface plot).

The best response in terms of welfare loss is achieved when the monetary rule is aggressive in both responding to output fluctuations and managing inflation expectations. That situation occurs when the weight on output is at maximum at 0.3 and the weight on inflation is at 0.24. The path of the nominal interest rate (Fig. 3) shows that the monetary authority is required to bring it down gradually before slowly raising it. Inflation is thus initially accommodated; then, as energy price starts its downward path, the interest rate slowly drops to stimulate output. As energy price drops further and the pressure on inflation increases, the interest rate slowly rises to tighten up the monetary response. Solely focusing on inflation yields less volatility in inflation but higher volatility in output. A policy that is aggressive in fighting both inflation and output fluctuations appears to provide the best trade-off between the volatilities of the two variables.

The responses of the economy to this wide range of monetary regimes are understood by examining the source of the energy price shock. When energy price jumps due to a real decline in energy supply, the real price of energy relative to durables and non-durables surges, and real marginal costs of capital of the producers are pushed up. Aggregate supply shrinks, leading to a drop in output. Fig. 4 shows the impact of this shock without monetary intervention. The presence of nominal price rigidities means that non-energy producers are even more sluggish in adjusting their prices to keep up with the energy price increase, making the increase in real marginal costs worse than in the case of full price flexibility. Because the household is also affected by the negative income effect due to higher energy price, aggregate demand also shifts leftward (Fig. 5). Thus, this energy price increase results in the contraction of both demand and supply. A strict price stability regime is forced to raise the interest rate right after the shock hits to fight the rising price level. However, because a large part of this upward pressure on marginal costs is due to the surge in the real price of energy, a desirable reduction in real marginal costs can only come from engineering a reduction in energy price relative to other prices. Raising the interest rate engenders a reduction in the relative price of energy indirectly through deflating the prices of non-energy goods by contracting aggregate demand, but this action turns out to be too broad and too aggressive, causing aggregate demand, and hence output and welfare, to drop even further (Fig. 6).

The optimal monetary policy response to this shock would be to push up aggregate demand already depressed by higher energy price. In doing so, the producers are forced to operate at an even higher level of marginal costs, and inflation is pushed up further. However, as demand is forced to shift back to the right, the drop in output and consumption is lessened (Fig. 7). The trade-off is precisely the opposite of a restrictive monetary stance. The real price of energy rises slightly higher, but the benefit to welfare outweighs this cost.

Focusing solely on variations in output, however, results in the interest rate dropping too much too quickly, causing an excessive stimulus to aggregate demand. With a sole, strong focus on output, in the subsequent periods, the monetary policy is then forced to bring the interest rate back up quickly. This course of action thus actually leads to more volatility in output and inflation. Figure 8 illustrates the volatility brought about by a sole focus on output.

Our results deviate from those of Leduc and Sill (2004), which called for price stability as the weapon of choice against such shocks. They showed that increasing the weight on output always amplifies the negative effect of the shock, whereas increasing the weight on inflation always does the opposite, regardless of the weight on the other coefficient. Our results shows that increasing the weight on inflation does not always lead to lower welfare losses, but rather only in cases in which the weight on output is sufficiently high, and that increasing the weight on output actually always leads to lower welfare losses. For us, consequently, a hawkish stance on inflation should not be without a strong focus on output. This main distinction between our findings and those of Leduc and Sill (2004) stems from the exogenous nature of oil price in their framework. An oil price increase in such a nominal environment does not necessarily reflect a real disturbance coming from a shrink in the oil supply. As Nakov and Pescatori (2010) stated, such a shock is observationally equivalent to a negative TFP shock, and a 'divine coincidence' occurs for the monetary authority when it tries to stabilize prices.

Our findings are more in line with Bodenstein et al. (2008), who found that an aggressive inflation-targeting regime is not helpful in terms of welfare and that a balanced, 'dual-mandate' regime performs well relative to the optimal policy. Our results, similar to theirs, lean toward output stabilization. Nakov and Pescatori (2010), although also using welfare as the criterion for evaluating alternative monetary regimes, did not come to conclusions similar to those of Bodenstein et al. (2008). They did stress that a strict price stability regime deviates from an optimal policy but did not go as far toward output stabilization. Their distinction from our results also rests on several points about the relative merits of alternative policies. In Nakov and Pescatori (2010), a baseline Taylor rule performs worse than does a more aggressive inflation-fighting policy or a strict inflation targeting policy. They also found that an interest rate peg regime is the worst of all, not only in terms of welfare but also in terms of inflation and output contraction and volatility. Our analyses come to opposite conclusions on both of these points. Furthermore, according to their results, the best policy in the class of Taylor rules using observed instruments is one that responds positively to oil prices. However, that would mean raising the interest rate as though fighting inflation, a stance that our results do not advocate. In relation to Kormilitsina (2011), our results agree that inflation should be allowed to rise. However, Kormilitsina's (2011) prescription of a higher nominal interest rate does not include anything more specific on actual optimal monetary rules.

5.2 TPF shock to non-energy producers

The picture is different for the case of a positive productivity shock to the non-energy sectors. Such a supply shock could cause energy price to increase, although it would lead to a drop in non-energy prices and the general price level. This energy price increase reflects a broad, indirect demand shock to the energy market as the household consumes and invests more in durables and the producers use more capital in production (Fig. 9). Figure 10 shows the welfare loss corresponding to each combination of (α_π, α_y), and Table 4 shows the welfare losses of selected regimes: price-stability, output-stability, interest-peg and the best-performing regime.

Regimes	**Welfare Gain (%)**
Max price-stability	5.28
Max output-stability	4.19
Interest-peg	4.45
Best-performing ($\alpha_\pi = 0.24$, $\alpha_y = 0$)	8.61

Table 4: Performance of various monetary regimes.

For this shock, aggressively responding to inflation/deflation appear to be the most effective means of accommodating the expanding business cycle, ensuring the highest gain in welfare. In contrast to the energy supply shock, as more weight is placed on output, welfare gain decreases. Again, responding solely to output does not bring meaningful variations in welfare gain.

The main distinction from the case of energy supply shock comes from the comovements between output and energy price and between inflation and energy price. The economy benefits from a rightward shift in aggregate supply, leading to an expansion in output (Fig. 9). Therefore, the optimal response is to bring aggregate demand up slowly to catch up. An inflation-focused monetary objective in this case serves that purpose. This causes energy price to rise higher, but the expansionary monetary stance quickly stabilizes the price level as well (Fig. 11).

Focusing only on output results in a rise in the interest rate that puts a brake on the expansion. This brake has the immediate effect of dampening consumption and investments (Fig. 12), leading to deeper drops in real marginal costs, because the producers must balance increased productivity with a more slowly growing demand. But this also means that the household is transferring its current consumption to the future as it seeks to invest its income in bonds. This transfer comes at a time when higher productivity is causing output, and consequently household income, to grow. This pressure is instead transferred into excess bond holdings. After the inter-temporal effects of increasing the interest rate have been in play for a few quarters, they start to bring higher income to the household. Therefore, as the momentum of a supply increase slows, demand starts its own upward momentum. However, the effects of the higher interest rate also include lower investment in capital. Thus, in the initial period of the supply expansion, capital build-up is slower; a smaller proportion of the expanding output is transferred into capital for future production. Thus, higher weights on output cause a greater dampening of demand at the start but greater demand momentum later, resulting in higher volatility in output, consumption and investments (Fig. 12), and they also cause a portion of output growth to be lost because of an inefficient build-up of capital.

A prescription for monetary policy thus calls for a strong take on inflation. The interest rate is kept slightly lower than its steady state for a long period to sustain the productivity increase (Fig. 11). This interest rate path has the effect of releasing most of the deflationary pressure because it allows demand to shift quickly to meet the increase in supply. Consequently, we have smoother responses for all of the macro variables, and prices are thus allowed to slowly decline over the period of higher productivity.

The optimal policy results from this section as well as from section 5.1 highlight the crucial consideration that is a common theme in dealing with energy price shocks: the trade-off between the immediate effect on aggregate demand of a monetary response and its longer-term, inter-temporal effect, particularly on capital.

5.3 Energy market-specific Demand Shocks

The endogenous energy production and convex costs allow us to analyze the macroeconomic effects of demand shocks to the energy market, because they create a mechanism for large energy price responses and a much less responsive energy supply, a stylized fact about energy observed in the data. The two energy market-specific demand shocks analyzed here are a shock to the household energy intensity of durables, represented by the parameter a, and a shock to the producer energy intensity of capital, represented by the parameter b. Figures 13 and 14 show the welfare losses corresponding to each combination of (α_π, α_y) for the two shocks, with the magnitude of each shock calibrated at 10% of the steady-state intensities, and Table 5 shows the welfare losses of selected regimes: price-stability, output-stability, interest-peg and the best-performing regime.

	Max price	Max output	Interest peg	Best performing
Welfare Gain (%)	-14.2	-13.1	-13.2	-12.1
Welfare Gain (%)	-23.2	-21.2	-21.5	-18.2

Table 5: Row 1: shock to energy intensity of durables, 14.9% energy price increase. Row 2: shock to energy intensity of capital, 27.1% energy price increase.

Qualitatively, these two shocks call for policy responses similar to the case of an energy supply shock. The overall effect on aggregate demand of these two shocks is contractionary due to the large negative income effect that higher energy price has on durable and non-durable consumption. The effect of higher energy price also spills over to the supply side, because energy is an input into production. Therefore, with both demand and supply contracting, the situation is similar to the case of an energy supply shock. Energy price and output again have a negative relationship, and real energy price and inflation move together. In such cases, the call again is for a strong focus on output to stimulate demand and to let inflation rise at the start, but at the same time maintaining a tight rein on inflation to avoid excess stimulation and high output volatility.

What distinguishes these two shocks from the usual energy supply crunch is the relative effectiveness of the monetary response. The relative extent of the effect of an energy price increase on demand and supply varies strongly between these two shocks. It is thus expected that, quantitatively at least, there would be varying degrees in the influence of monetary policy in response to these shocks. Table 5 shows that monetary policy response does not lead to the same welfare losses (in terms of energy price elasticity) between these two shocks. Of the three adverse shocks, the shock to the energy intensity of durables causes the worst welfare losses under all monetary regimes, whereas the shock to the energy intensity of capital is similar to the energy supply shock in its effect on welfare. As explained in Huynh (2015), the demand shock coming from the increase in the energy intensity of durables has a disproportionately greater effect on aggregate demand. The reason is the presence of an amplification mechanism on the demand side in the case of this shock. When the household durable stock is more energy-intensive, the impact of the demand shock goes beyond energy price because the increased cost of durable investment and utilization is reflected by more than just energy price. The energy price elasticities of household consumption and investment (with the exception of capital investment) in this case are greater in magnitude than either the energy supply shock or the shock to the energy intensity of capital. As a result, aggregate demand is shifted left by a greater extent compared with the other two shocks, causing a larger negative impact on household welfare.

Thus, it is expected that the benefit of the best performing regime is smaller for a demand shock coming from an increase in the energy intensity of durables. The greater pressure of high energy price on durable consumption causes the expansionary monetary regime to be less effective at expanding aggregate demand. Conversely, the demand shock coming from a higher energy intensity of capital has a relatively greater effect on aggregate supply, since the amplification of the shock is on the producers. Without as much pressure on the household, as a result, an output-stabilization regime is able to stimulate demand to a greater extent.

The two demand shocks to the energy market show important quantitative differences in their effect on the business cycle and in their interactions with monetary responses.

These distinctions come from the different degrees of effect on the demand and supply sides of the economy and the diverse relocations of resources in accordance with the sources of the shocks. As a result, the effectiveness of monetary intervention varies between the two shocks. The need here is to be mindful of this fact to avoid going too little or too far in devising the appropriate responses.

6 Role of Sectoral Price Rigidities

In the baseline calibration of the model, the two non-energy sectors have the same degree of price rigidity. Given the different degrees of energy dependency between the consumption of durables and non-durables, it is natural to pose the question as to whether there is a difference in the sensitivity of the business cycle to these price rigidities in the event of energy price shocks. For this investigation, we ran the model along a two-dimensional grid containing values of price rigidities of the durable and non-durable sector. Throughout this exercise, the monetary policy function is kept at the baseline Taylor-type specification. Figures 15 and 17 display the output responses to the energy supply shock and the TFP shock to the non-energy producers at three degrees of non-durables' price rigidity relative to that of durables: more flexible ($\vartheta_n = 1$), as sticky ($\vartheta_n = 46$), and more sticky ($\vartheta_n = 86$), whereas Figures 16 to 18 show the output responses to these two shocks at three degrees of durables' price rigidity relative to that of non-durables: more flexible ($\vartheta_d = 1$), as sticky ($\vartheta_d = 46$), and more sticky ($\vartheta_d = 86$).

The graphs show that the price rigidity of the durable sector plays a greater role in transmitting energy price shocks. Output (value added) displays a higher sensitivity to variation in this price rigidity for both shocks. The main explanation is in the more volatile response of the durable sector. Nondurables become 'anchor' goods in periods of energy price fluctuations; thus, their consumption shows much less sensitivity than does durable (and capital) consumption to energy price changes. Another reason is that the response of the non-durable sector shows a higher sensitivity to variations in durables' price rigidity than vice versa. Consequently, when the price rigidity of durables varies, both durable and non-durable output displays considerable sensitivity. Conversely, when the price rigidity of non-durables changes, the sensitivity of durable output is smaller.

This asymmetry in how price rigidity in one sector affects consumption/output of the other sector's goods is a direct consequence of the different degrees of energy dependence between these two types of goods. As energy price rises, it triggers a substitution effect that moves the household from more energy-dependent goods toward less energy-dependent goods, while consumption of both these goods drops due to the income effect. Consumption of durables thus moves much more strongly than the consumption of non-durables. Upon the impact of energy price shocks, the household moves to a point of consumption at which the marginal utility of durable consumption is much greater than that of non-durable consumption. Greater flexibility in the prices of more energy-dependent goods, meaning the initial surge in their prices is higher, reinforces the move toward less energy-consuming goods but also requires the household to acquire a relatively large quantity of non-durables for a small marginal reduction in durable consumption. Non-durable consumption is therefore highly sensitive to the price stickiness of durables. Conversely, when prices of non-durables are more flexible, the move back toward durable consumption simply does not occur with the same magnitude, because the household is willing to give up a large margin of non-durables for a relatively smaller marginal gain in durable consumption. Thus, durable consumption and output do not exhibit the same sensitivity to nondurables' price rigidity.

7 Conclusion

This paper employs a New Keynesian model with endogenous energy production to extend the analysis on the role of monetary policy in the event of shocks to the energy market. The framework makes use of convex costs in energy production to create dynamics of energy supply and energy price that come close to empirical observations. This convex cost feature and the presence of multiple sectors represent a marked departure from previous theoretical works on the subject.

Our findings show a number of distinctions from and agreements with results from previous works in the case of energy supply shocks. We lean toward output stabilization, as did Bodenstein et al. (2008), with an appropriate degree of price stability to avoid excessive volatility in output and prices. Our results run counter to Leduc and Sill (2004) and Nakov and Pescatori (2010), who found strong inflation fighting regimes more desirable. We agree with Kormilitsina (2011) that inflation should be accommodated, but since her conclusion was unclear on the degree of output stimulation to pursue, our results went further in prescribing the policy that should accompany this inflation-accommodating stance.

We also shed light on the effect of alternative monetary regimes in the events of other types of energy price shocks, such as a TFP shock that raises aggregate demand and demand shocks specific to the energy market. An aggregate shock such as the TFP shock requires a wholly distinct policy reaction. In this case, the optimal policy favors price stability. The two energy market-specific demand shocks need policy interventions that are qualitatively similar to the case of an energy supply shock, but they do highlight important quantitative differences that cause the impact/effectiveness of various monetary regimes to vary between them. In none of these shocks, however, does a desirable monetary response entail responding positively to energy price, in terms of minimizing welfare loss.

The explicit modeling of goods with different degrees of energy dependency allowed us to gain important insights into the inter-sectoral dynamics. When a shock is more confined to the energy market, a surge in the price of energy relative to other goods can be very large, and the energy price shock hits energy-dependent goods and non-energy-dependent goods quite differently. The durable sector suffers comparatively more on its demand side than does the non-durable sector, which is affected primarily through its supply side. Our analysis on sectoral price rigidities indicates that the degree of price stickiness of more energy-dependent goods plays a greater role in the propagation of energy price shocks because the behavior of the less energy-dependent goods sector is more sensitive to this price rigidity than vice versa.

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Tables and Figures

Moments	Values
E_h/Y	0.0456
I_d/Y	0.0932
D/Y	1.3668
E_f/Y	0.0517
K/Y	12.000
H	0.3000

Table 6: Targeted Ratios

The aggregates present in the ratios are real GDP (Y), household's and production energy usages (E_h and E_f respectively), durables consumption (I_d), durables and capital stock (D and K), and labour (H). They each have a broadly corresponding theoretical counterpart in the model of Dhawan and Jeske (2008). Since in these variables our model matches the model of Dhawan and Jeske (2008) quite closely, these ratios provide good empirical bases with which to calibrate the theoretical moments of these variables in our model.

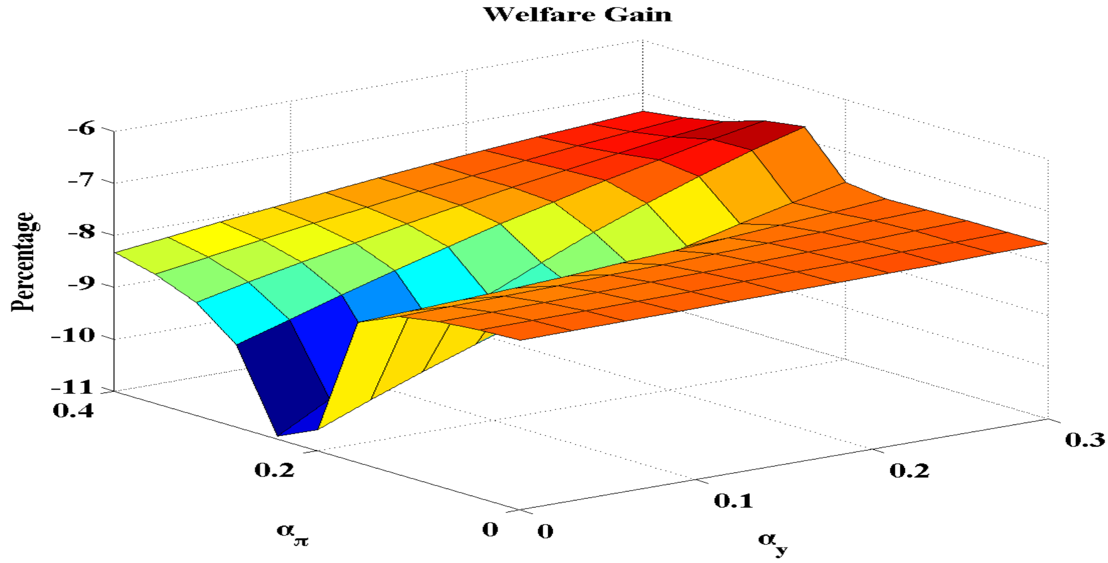

Figure 1: Welfare gain in the case of a negative productivity shock to the energy sector.

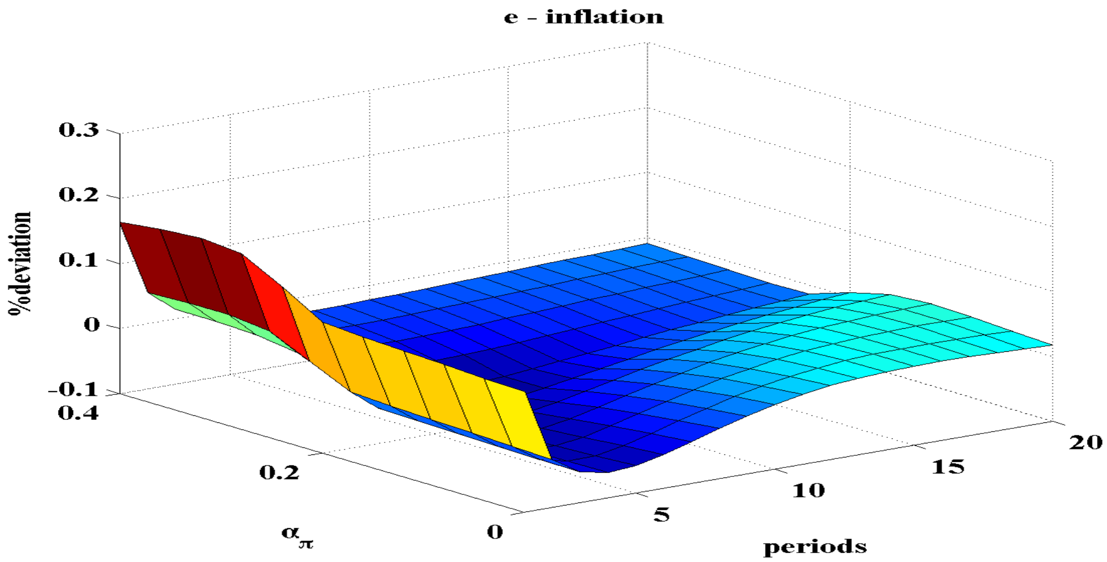

Figure 2: Response of inflation at $\alpha_y = 0.3$.

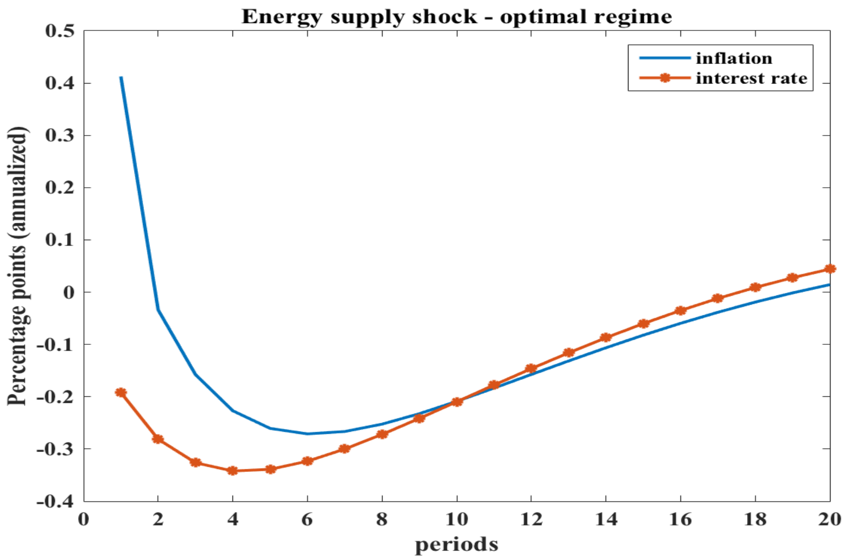

Figure 3: Inflation and interest rate in response to energy supply shock with welfare-maximizing monetary regime.

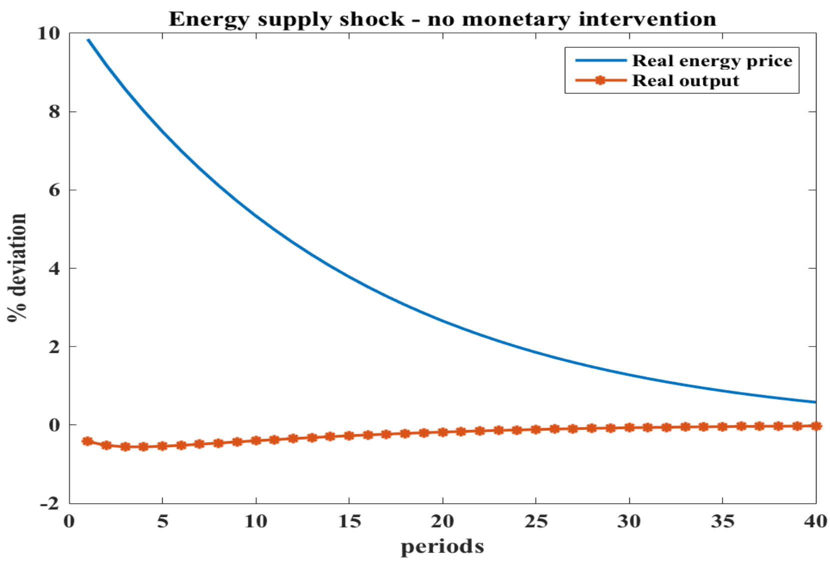

Figure 4: Impact of energy supply shock without monetary intervention.

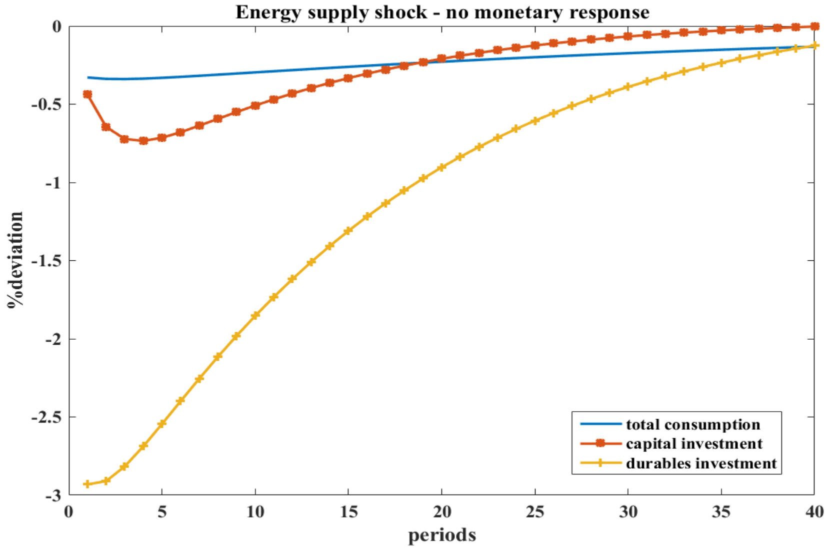

Figure 5: Impact of energy supply shock without monetary intervention.

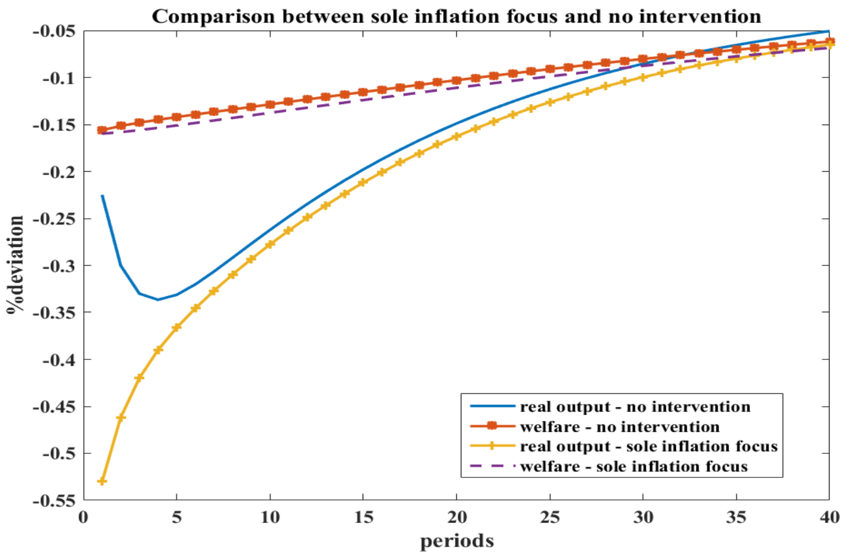

Figure 6: Comparison of output and welfare between sole inflation focus and no monetary intervention in the case of energy supply shock.

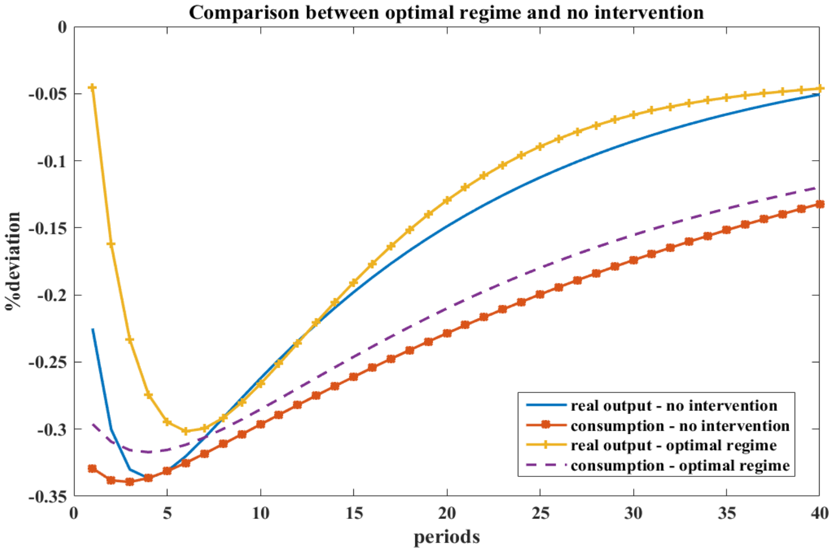

Figure 7: Comparison of output and consumption between optimal monetary regime and no monetary intervention in the case of energy supply shock.

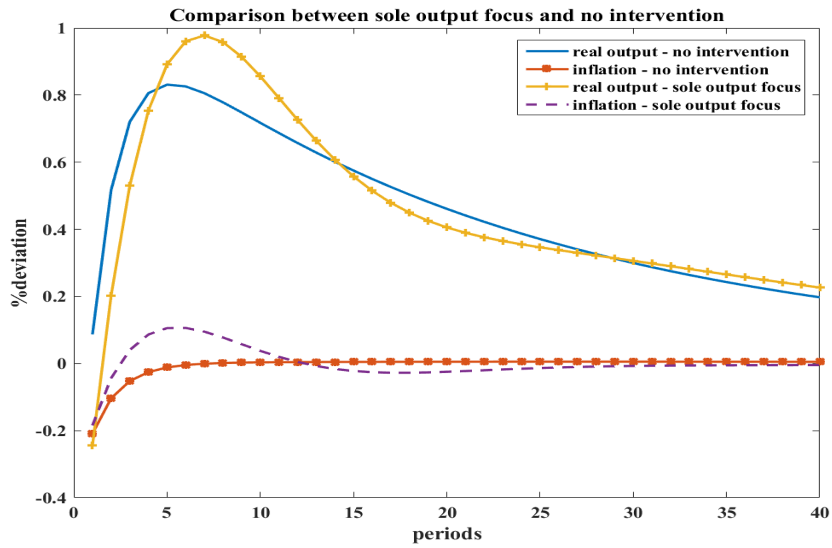

Figure 8: Comparison of output and inflation between sole output focus and no monetary intervention in the case of energy supply shock.

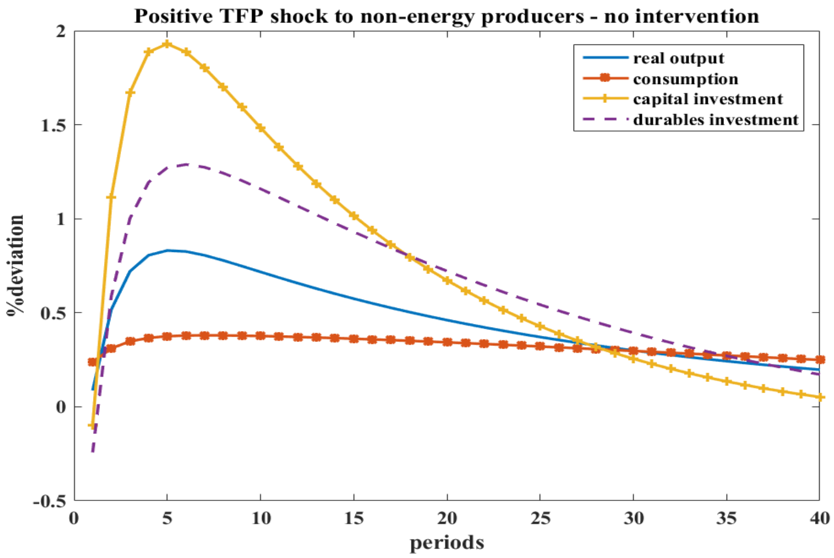

Figure 9: Impact of a positive TFP shock to non-energy producers without monetary intervention.

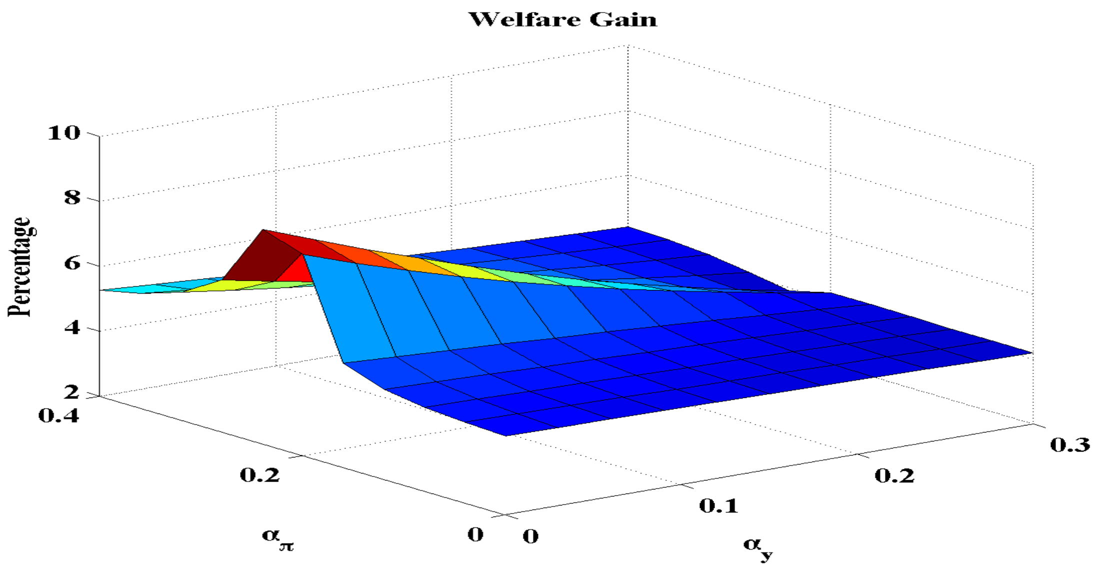

Figure 10: Welfare gain in the case of a positive TFP shock to the non-energy sectors.

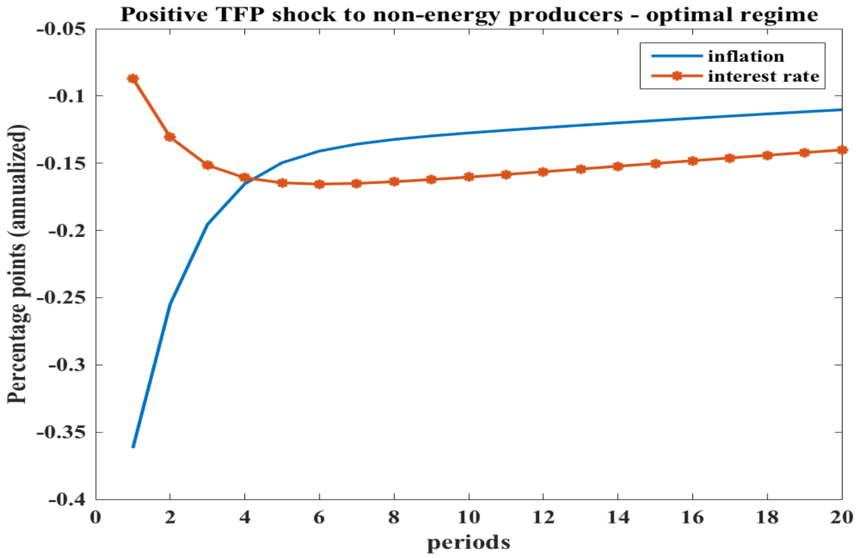

Figure 11: Inflation and interest rate in response to a positive TFP shock to non-energy producers with welfare-maximizing monetary regime.

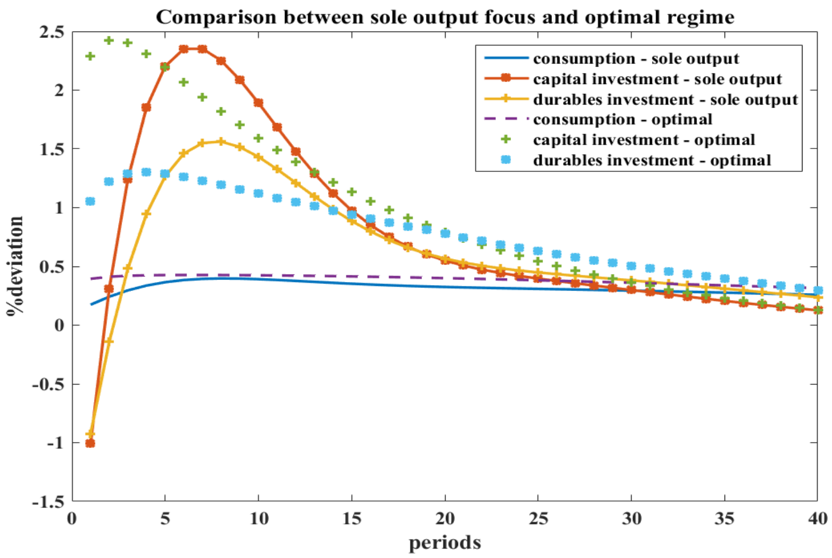

Figure 12: Comparison of investments and consumption between optimal monetary regime and sole output focus in the case of a positive TFP shock to the non-energy producers.

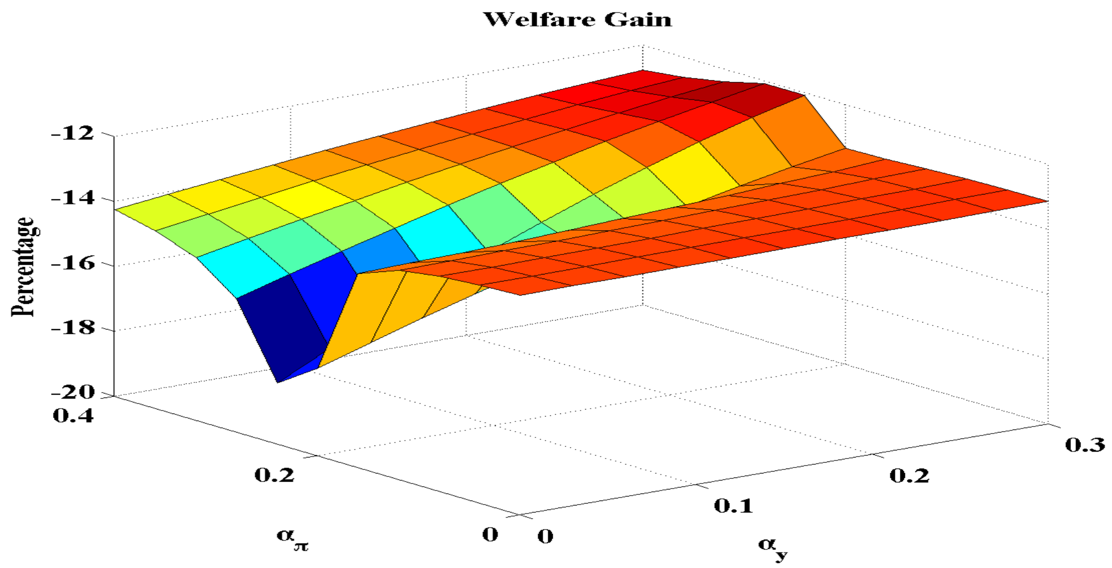

Figure 13: Welfare gain in the case of a positive shock to the energy intensity of durables.

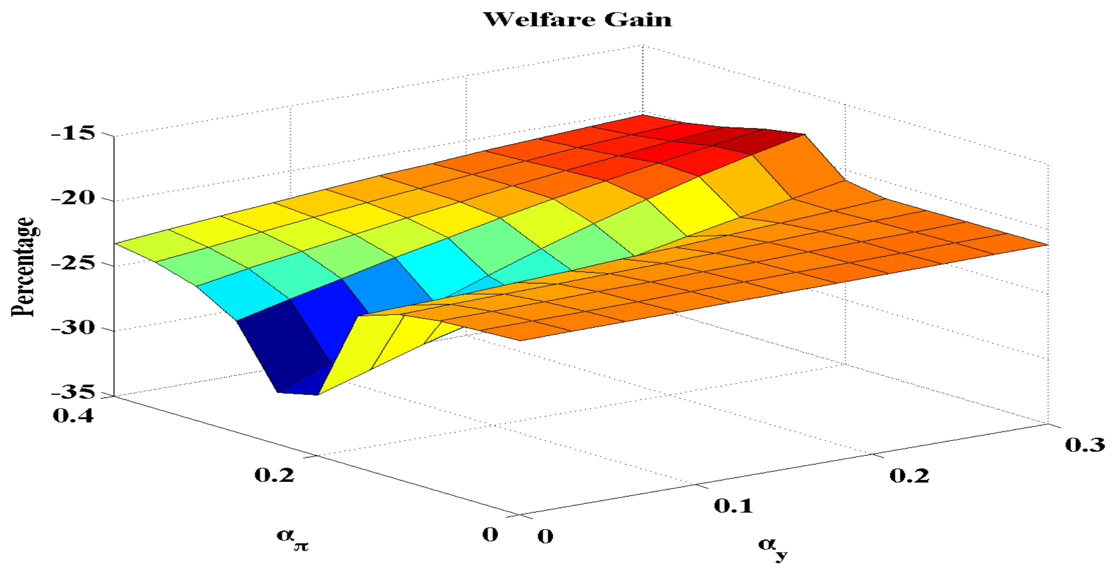

Figure 14: Welfare gain in the case of a positive shock to the energy intensity of capital.

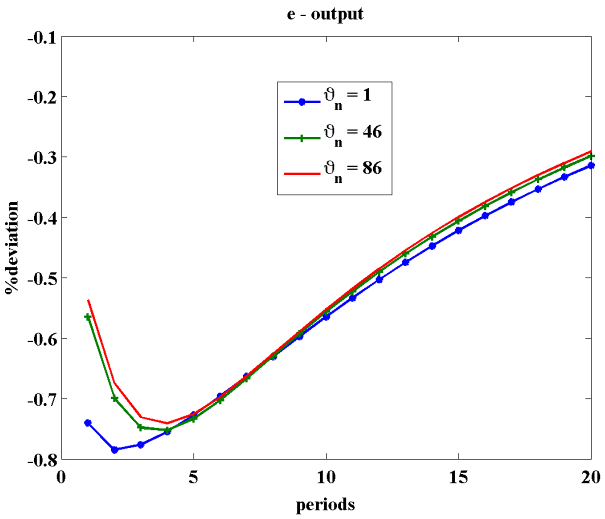

Figure 15: response of output to energy supply shock at three degrees of non-durables price rigidity under baseline Taylor rule

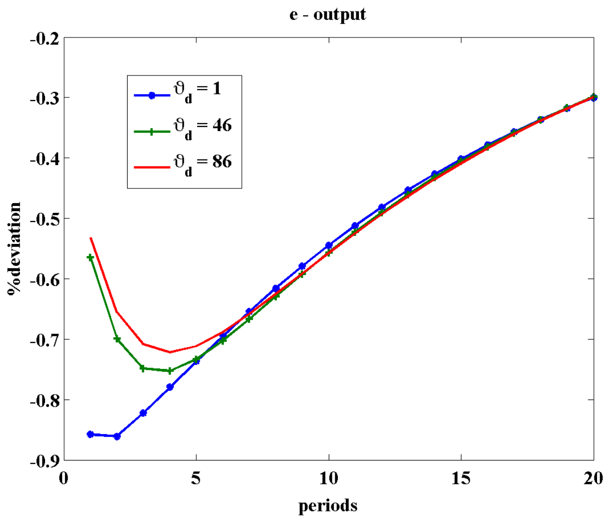

Figure 16: response of output to energy supply shock at three degrees of durables price rigidity under baseline Taylor rule

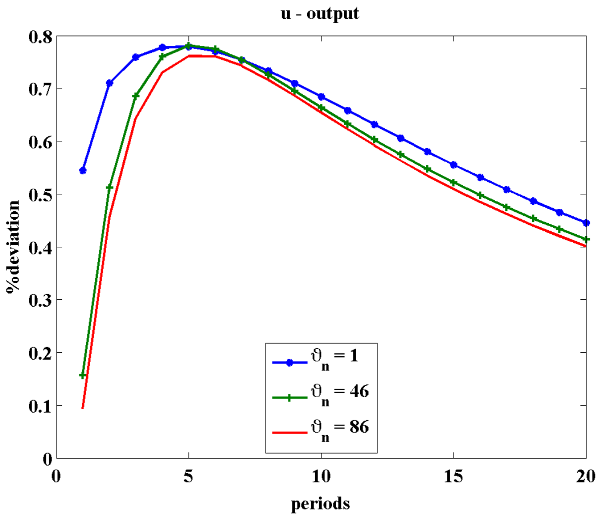

Figure 17: response of output to a positive TFP shock to non-energy producers at three degrees of non-durables price rigidity under baseline Taylor rule

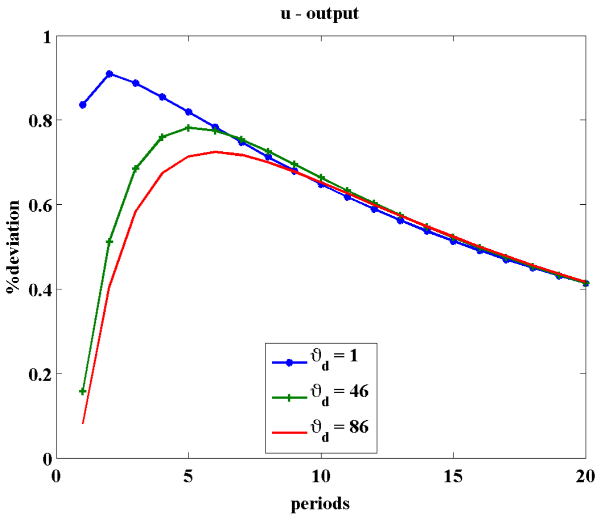

Figure 18: response of output to a positive TFP shock to non-energy producers at three degrees of durables price rigidity under baseline Taylor rule

Appendices

A Table of Calibrated Parameters

Table 7:
Calibrated Parameters

Parameter	Value	Description
β	0.99	Discount factor
φ	0.34	Share of consumption in household's utility
α	0.2	Share of durables in household's consumption
ρ	1 - 1/0.99	Durables-nondurables CES parameter
δ_k	0.015	Capital depreciation rate
a_1	0.055	Param1 of durables depreciation function
a_2	0.3	Param2 of durables depreciation function
γ_{e1}	0.60	Capital share of energy production function
γ_{d1}	0.34	Capital share of durables production function
γ_{n1}	0.38	Capital share of nondurables production function
ω_{k1}	3	Param1 of capital adj. cost function
ω_{k2}	1	Param2 of capital adj. cost function
ω_{d1}	6	Param1 of durables adj. cost function
ω_{d2}	1	Param2 of durables adj. cost function
ω_{B1}	0.001	Param1 of portfolio adj. cost function
ω_{B2}	1	Param2 of portfolio adj. cost function
$\bar{B}$	1.2	Bond target in PAC function
ω_{e1}	3.77	Param1 of energy convex cost function
ω_{e2}	2	Param2 of energy convex cost function
ϵ_d	5	Elasticity of substitution among varieties of durables
ϵ_n	5	Elasticity of substitution among varieties of nondurables
ϕ_d	46	Price adjustment cost parameter for durables
ϕ_n	46	Price adjustment cost parameter for nondurables
a	0.06	Energy intensity of durables
b	0.012	Energy intensity of capital
α_r	0.8	Lagged interest rate coefficient of the monetary rule
α_π	0.2	Inflation coefficient parameter of the monetary rule
α_y	0.09	Output coefficient parameter of the monetary rule
$\bar{\pi}$	1	Steady-state gross inflation
g	0.18	Steady-steady share of government spending
τ_c	0.07	Steady-state consumption tax
τ_i	0.15	Steady-state income tax
$\tau_{e,c}$	0.10	Steady-state energy tax on households
$\tau_{e,f}$	0.10	Steady-state energy tax on producers
ρ_c	0.08	Lagged tax rate coefficient of the consumption tax rule
ρ_i	0.08	Lagged tax rate coefficient of the income tax rule
$\rho_{e,c}$	0.08	Lagged tax rate coefficient of the energy tax rule for consumers
$\rho_{e,f}$	0.08	Lagged tax rate coefficient of the energy tax rule for producers
ϕ_c	0.12	Bond coefficient of the consumption tax rule
ϕ_i	0.12	Bond coefficient of the income tax rule
$\phi_{e,c}$	0.12	Bond coefficient of the energy tax rule for consumers
$\phi_{e,f}$	0.12	Bond coefficient of the energy tax rule for producers
ρ_{A1}	0.95	Persistence of shock to energy suppy
ρ_{e1}	0.95	Persistence of TFP shock to non-energy producers
ρ_a	0.95	Persistence of shock to energy intensity of durables
ρ_b	0.95	Persistence of shock to energy intensity of capital
$\sigma_{e,t}$	0.021	Standard error of shock to energy supply
$\sigma_{A,t}$	0.0065	Standard error of TFP shock to non-energy producers
$\sigma_{a,t}$	0.0006	Standard error of shock to energy intensity of durables
$\sigma_{b,t}$	0.0012	Standard error of shock to energy intensity of capital

B Equilibrium Conditions

Household's first order conditions

Euler equation for durables

$$(1-\alpha)^{1-\rho}\tfrac{p_{d,t}}{p_{n,t}}c_t^{-\rho}n_t^{\rho-1}\left(1+\tfrac{\omega_{d1}}{d_t}\left(\tfrac{d_{t+1}-d_t}{d_t}\right)^{\omega_{d2}}\right)=\beta E\alpha^{1-\rho}c_{t+1}^{-\rho}(u_{t+1}d_{t+1})^{\rho-1}u_{t+1}$$
$$+\beta E\tfrac{(1-\alpha)^{1-\rho}}{(1+\tau_{c,t+1})p_{n,t+1}}c_{t+1}^{-\rho}n_{t+1}^{\rho-1}[-ap_{e,t+1}(1+\tau_{e,c,t+1})u_{t+1}$$
$$+(1+\tau_{c,t+1})p_{d,t+1}\left(1-\delta_{d,t+1}+\tfrac{\omega_{d1}d_{t+2}}{d_{t+1}^2}\left(\tfrac{d_{t+2}-d_{t+1}}{d_{t+1}}\right)^{\omega_{d2}}\right)]$$

Euler equation for capital

$$\tfrac{p_{d,t}}{(1+\tau_{c,t})p_{n,t}}c_t^{-\rho}n_t^{\rho-1}\left(1+\tfrac{\omega_{k1}}{k_t}\left(\tfrac{k_{t+1}-d_t}{k_t}\right)^{\omega_{k2}}\right)=$$
$$\beta E\tfrac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{(1+\tau_{c,t+1})p_{n,t+1}}[(1-\tau_{i,t+1})r_{t+1}+p_{d,t+1}\left(1-\delta_k+\tfrac{\omega_{k1}k_{t+2}}{k_{t+1}^2}\left(\tfrac{k_{t+2}-k_{t+1}}{k_{t+1}}\right)^{\omega_{k2}}\right)]$$

Euler equation for bond

$$\frac{c_t^{-\rho}n_t^{\rho-1}}{(1+\tau_{c,t})p_{n,t}}\left(1+\omega_{B1}\left(B_{t+1}-\bar{B}\right)^{\omega_{B2}}\right)=\beta E(1+R_{t+1})\frac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{(1+\tau_{c,t+1})p_{n,t+1}}$$

Intra-temporal nondurables-labor

$$(1-\alpha)^{1-\rho}\frac{\varphi}{1-\varphi}(1-h_t)c_t^{-\rho}n_t^{\rho-1}=\frac{(1+\tau_{c,t})p_{n,t}}{(1-\tau_{i,t})w_t}$$

Intra-temporal nondurables-utilization

$$\frac{(1-\alpha)^{1-\rho}}{\alpha^{1-\rho}}\frac{n_t^{\rho-1}}{(u_t d_t)^{\rho-1}}=\frac{(1+\tau_{c,t})p_{n,t}}{a(1+\tau_{e,c,t})p_{e,t}+(1+\tau_{c,t})p_{d,t}\delta'_{d,t}}$$

with

$$c_t=[\alpha^{1-\rho}(u_t d_t)^\rho+(1-\alpha)^{1-\rho}{n_t}^\rho]^{1/\rho}$$

Budget constraint

$$(1+\tau_{e,c,t})p_{e,t}au_t d_t+(1+\tau_{c,t})p_{n,t}n_t+(1+\tau_{c,t})p_{d,t}i_{d,t}+p_{d,t}i_{k,t}+i_{B,t}$$
$$=(1-\tau_{i,t})(w_t h_t+r_t k_t)+R_t B_t$$

Investment adjustment costs and variable depreciation

$$i_{d,t}=d_{t+1}-(1-\delta_{d,t})d_t+\frac{\omega_{d1}}{1+\omega_{d2}}\left(\frac{d_{t+1}-d_t}{d_t}\right)^{1+\omega_{d2}}$$

$$i_{k,t}=k_{t+1}-(1-\delta_k)k_t+\frac{\omega_{k1}}{1+\omega_{k2}}\left(\frac{k_{t+1}-k_t}{k_t}\right)^{1+\omega_{k2}}$$

$$i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B1}}{1+\omega_{B2}}\left(B_{t+1} - \bar{B}\right)^{1+\omega_{B2}}$$

$$\delta_{d,t} = \frac{a_1}{a_2+1} {u_t}^{a_2+1}$$

Sectors' aggregate outputs

$$y_{e,t} = exp(A_{e,t}) k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e}$$

$$b_{e,t} = \frac{\omega_{e1}}{(1+\omega_{e2})}(k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}}$$

$$y_{i,t} = exp(A_t)\,(k_{i,t})^{\gamma_i}\,(h_{i,t})^{1-\gamma_i} - \chi_i$$

with $i = d, n$

Firms' first order conditions

$$mc_{i,t} exp(A_t)(1-\gamma_i)\left(\frac{k_{i,t}}{h_{i,t}}\right)^{\gamma_i} = \frac{w_t}{p_{i,t}}$$

$$\frac{1-\gamma_i}{\gamma_i}\frac{k_{i,t}}{h_{i,t}} = \frac{w_t}{r_t + b p_{e,t}(1+\tau_{e,f,t})}$$

$$p_{e,t} exp(A_{e,t})\gamma_e\left(\frac{k_{e,t}}{h_{e,t}}\right)^{\gamma_e-1} = r_t + b_{e,t}p_{e,t}(1+\tau_{e,f,t}) + k_{e,t}p_{e,t}(1+\tau_{e,f,t})b'_{e,t}h_{e,t}^{1-\gamma_e}\gamma_e k_{e,t}^{\gamma_e-1}$$

$$p_{e,t} exp(A_{e,t})(1-\gamma_e)\left(\frac{k_{e,t}}{h_{e,t}}\right)^{\gamma_e} = w_t + k_{e,t}p_{e,t}(1+\tau_{e,f,t})b'_{e,t}h_{e,t}^{-\gamma_e}(1-\gamma_e)k_{e,t}^{\gamma_e}$$

Sectoral Phillips curves

$$\hat{\pi}_{i,t} = \beta E_t[\hat{\pi}_{i,t+1}] + \frac{\epsilon_i - 1}{\vartheta_i}\hat{mc}_{it}$$

with $i = d, n$

Fiscal and monetary policies

Government budget constraint

$$\tau_{e,c,t}p_{e,t}au_t d_t + \tau_{e,f,t}p_{e,t}(b(k_{d,t}+k_{n,t}) + b_{e,t}k_{e,t}) + \tau_{c,t}(p_{n,t}n_t + p_{d,t}i_{d,t}) + \tau_{i,t}(r_t k_t + w_t h_t)$$
$$+ i_{B,t} = p_t g_t y_t + R_t B_t$$

Tax rules

$$log\left(\frac{\tau_{(),t}}{\bar{\tau}_{()}}\right) = \rho_{()} log\left(\frac{\tau_{(),t-1}}{\bar{\tau}_{()}}\right) + \phi_{()} log\left(\frac{B_t}{\bar{B}}\right) \quad (38)$$

with $() = (e,c), (e,f), c, i$

Monetary policy function

$$R_t - R^* = \alpha_R(R_{t-1} - R^*) + \alpha_\pi(\pi_t - \pi^*) + \alpha_y(y_t - y_{t-1}) + \epsilon_{r,t}$$

Market clearing

$$k_t = k_{d,t} + k_{n,t} + k_{e,t}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t}$$

$$y_{d,t} = i_{d,t} + i_{k,t} + g_{d,t} + \frac{\vartheta_d}{2}(\pi_{d,t} - 1)^2 y_{d,t}$$

$$y_{n,t} = n_t + g_{n,t} + \frac{\vartheta_n}{2}(\pi_{n,t} - 1)^2 y_{n,t}$$

$$g_t y_t = \left[\alpha^{1-\rho} g_{d,t}^{\rho} + (1-\alpha)^{1-\rho} g_{n,t}^{\rho}\right]^{1/\rho}$$

$$p_t g_t y_t = p_{d,t} g_{d,t} + p_{n,t} g_{n,t} + p_{e,t} a g_{d,t}$$

Aggregate price and aggregate value added

$$p_t = \left[\alpha \left(p_{d,t} + a p_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha) p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}$$

$$p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t$$

Exogenous shock process

$$A_t = \rho_A A_{t-1} + \epsilon_{A,t}$$

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_{e,t}$$

$$g_t = \rho_g g_{t-1} + \epsilon_{g,t}$$