Monetary Policy and Energy Price Shocks

Bao Tan Huynh*
School of Economics†
Singapore Management University

October 2013

Abstract

A New Keynesian framework with endogenous energy production is proposed to investigate the role of monetary policies in dealing with disturbances in the 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 kinds 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 literature on dealing with energy supply shock. In addition we shed lights on inter-sectoral dynamics under the interaction between monetary policy and energy price shocks, as well as the role of sectoral price rigidities in the shocks’ propagation.

JEL classifications: C68, E32, E52, Q43.

Keywords: energy, energy price shock, DSGE model, monetary policy.

*Correspondence to: Bao Tan Huynh, School of Economics, Singapore Management University, 90 Stamford Road Singapore 178903, email: bthuynh.2010@phdecons.smu.edu.sg
†I sincerely thank my advisor Sungbae An for his invaluable guidance and endless patience.
1 Introduction

Research on the impact of oil price shocks on the economy has been extensive, from 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, firstly on whether and how much monetary policy exacerbates the negative effects of an oil price increase, and secondly 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, and the debate is far from settled. For instance, Leduc and Sill (2004) prescribe price stability as the policy of choice in dealing with energy (oil) supply shock, while the results from Bodenstein et al (2008) argue against this policy, opting instead for more output stabilization. At the same time there is also growing justification to go beyond oil and oil supply shocks, towards looking at energy as a whole and the possible different sources of energy price increases. As Kilian (2009) has pointed out, it is of crucial and practical importance to disentangle the different kinds of supply and demand shocks that could affect the energy markets and to distinguish their impacts, because not all energy price increases have the same underlying cause or should be treated equally. Complementing this conclusion is the empirical study of Baumeister and Peersman (2012), which found a smaller role of oil supply shocks in the variability of oil price over time, the implication of which is that oil price fluctuations have become more demand-driven, a finding echoed by Kilian (2008) in the historical decomposition of U.S. gasoline price. Viewed against these developments, the literature on monetary policy has not concerned itself with energy price increases resulted from shocks other than energy supply shock, thus leaving still unexplored other possible sources of energy price disturbances and whether one optimal monetary prescription may or should be applicable to them all.

The aim of this paper is to address the lack of consensus regarding the case of energy supply shock and the hitherto unanswered question of how monetary policy should respond to a wider set of energy price increases with the help of a New Keynesian DSGE framework with energy at its core. Its contribution is three-fold.

First, it joins the literature on monetary policy in the context of energy/oil supply shock, in which the works of Bernanke, Gertler and Watson (1997), Hamilton and Herrera (2004), Leduc and Sill (2004) and Kormilitsina (2011) have made major impact, and brings its own analyses to bear on the debate. The aim is to bring together the diverse conclusions on the desirable monetary conduct in response to oil/energy supply shock, especially those obtained from DSGE frameworks, and see whether our results allow us to put our weight on one side or the other of the inflation-output divide.

Second, we used the framework, built upon the RBC one-country model of Huynh (2012), to extend the question of desirable monetary responses to other kinds of shocks to the energy markets. The endogenous energy production feature brings a completeness to a theoretical model with energy at its core and allows energy production and energy prices to fully respond to economic conditions. The introduction of convex costs of energy production is crucial in this contribution as it helps create more realistic dynamics of energy price and energy supply in response to demand shocks to the energy market. As Huynh (2012) has pointed out, different kinds of energy price
shocks indeed leave distinct imprint on the business cycles. The focus here is on monetary policy, whether and how it is required to vary its response to different instances of energy price increases.

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 dependency (only in terms of their consumptions), we set out to investigate whether the relative price rigidity between the two sectors (durables and non-durables, as they are called in our model) plays an important role in determining the response of the economy to energy price shocks and to monetary policy reactions.

The model used for analysis in this paper is developed from the basic RBC framework of Huynh (2012), comprising a fully endogenous energy sector with convex costs in production, as well as durables and non-durables sectors. New Keynesian features are introduced, in the form of monopolistic competition and price rigidity for the durables and non-durables 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, in that it is augmented by the incorporation of energy production and consumption, and it is used for looking at 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/consumption in the household, thereby missing out on an important channel in terms of the direct income effect through which energy makes its impact on the demand side of the economy. Both Leduc and Sill (2004) and Kormilitsina (2011) also assumed an exogenous oil price process. In this kind of setup, all instances of energy related shocks are represented by an exogenous oil price increase, and are therefore considered to be the same in terms of their effects on the economy. In such 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), while 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), while endogenous, has too high price elasticity in the short run. For example, to engender a less than 10% increase in oil price the supply from the fringe producers drops by 20%, and the dominant oil producer increases output by 10%. 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

\(^1\)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
This mechanism of producing large energy price response and relatively smaller energy supply response is especially important for the analyses of demand shocks to the energy market, as without it, any shock to energy demand brings about unrealistically large expansion in energy supply and consequentially very low energy price increase.

In the context of monetary analysis with energy price shocks, our model also stands out from these frameworks by explicitly modeling the consumptions of goods with different degrees of energy-dependence\(^3\) and having separate production sectors for these goods. This introduces additional dynamics into the household's consumption behaviors in response to energy price increases and creates heterogeneity in the way these shocks impact the different goods sectors.

Our approach at analyzing the impact of monetary policy in events of energy price shocks also differs from Bodenstein et al (2008), Nakov and Pescatori (2010) and Kormilitsina (2011). We followed the approach of Leduc and Sill (2004) in that we compared the relative effectiveness of different monetary regimes with one another in terms of their impact on the business cycles, mainly output and consumption.

The four shocks studied in this paper follow those of Huynh (2012): productivity shock to the energy sector, representing the usual energy supply shock, TFP shock to the non-energy sectors, which is a kind of aggregate shock to energy demand, and two energy-market specific demand shocks coming from the household and the producers respectively.

Regarding the energy supply shock, our results differ from those before in several aspects, and find agreement in others. We do not find that price stability is the best in terms of minimizing the shock’s impact on output and consumption, in contrast to Leduc and Sill (2004). Our findings are more in line with Bodenstein et al (2008), as we lean towards output stabilization, even though we add to this with a caution against going too much towards output without a corresponding focus on inflation. The conclusions drawn from Nakov and Pescatori (2010) also differ from ours. While they did propose a certain degree of focus on output stabilization as an optimal form of monetary policy, their favorable view of strict price and aggressive inflation fighting policies are in contrast to what we obtained from our analyses.

Extending the analysis to other kinds of energy price shocks, we found that in the event of a positive TFP shock to non-energy producers, which increases the aggregate demand for energy, a strong focus on inflation is best in terms of ensuring the strongest expansion in output and consumption. We showed that this instance of energy price shock is very distinct from the one before, not just in terms of the responses of the economy to it but also in terms of the relative performance of alternative

---

\(^2\)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 (2012), 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.
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 required policy on stabilizing output and consumption varies between these two shocks, compared to the case of energy supply shock. This is due to the quantitatively distinct impact of each shock, especially on the durables sector.

We also showed how the energy-dependent goods and the non-energy-dependent goods are subjected to different degrees of inflationary pressure in the events of adverse energy price increases. These shocks can cause large increases in the relative price of energy, which impact the demand of energy-dependent goods disproportionately more. As a result inflation in the durables goods sector is comparatively lower than the non-durables goods sector because of this added deflationary pressure coming from the demand side. Furthermore, it is found that the price rigidity of the more energy-consuming goods plays a greater role in the propagation of energy price shocks. Output and consumption and many other macro variables show higher sensitivity to varying price stickiness of durables goods. Different degrees of durables’ price rigidity also influence the non-durables sector’s behavior more than vice versa. This is a consequence of the fact that the more energy-dependent goods sector always shows more volatile responses when energy price changes. Also it is due to the interplay between the substitution effect and the income effect that causes consumption of durables to vary little when the price of non-durables changes, but not vice versa.

The paper is organized as follows. A description of the model is given in section 2. Section 3 gives details on the model’s calibration. Section 4 reviews the response of the economy to energy price shocks under the baseline Taylor rule, and section 5 analyzes the impact on monetary shocks on energy prices. The comparative study of alternative monetary policy responses in events of energy price shocks is given in section 6. Section 7 provides an analysis on inter-sectoral dynamics, and section 8 concludes.

2 Model Description

2.1 Households

Consumption of durables and non-durables

Household consumes a CES aggregation of durables and non-durables of the following form

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

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 \( \frac{\alpha^{1-\rho}}{1-\rho} \). Together, \( u_t d_t \) defines the service the household derives from its existing stock of durables in period \( t \).

Household’s energy usage
Household’s use of durables needs energy, the amount of which \((e_{h,t})\) is variable in each period and directly dependent on the utilization rate and the stock of durables that the household has at the start of the period. As can be seen, energy consumption does not enter the utility function directly, but rather it is needed to enable the household to derive utility from the stock of durables that it has. Therefore the cost of energy used in the household enters into each period’s budget constraint. In this specification, the model makes use of the Energy-in-Cost method used by Finn (2000) and extends it to the household.

The amount of energy used in each period by the household can be thought to be a function of the stock of durables times its utilization rate
\[
e_{h,t} = f(u_{t}d_{t})
\]
In all analyses carried out in this paper the amount of energy needed to sustain a utilization rate \(u_{t}\) of a stock of durables \(d_{t}\) is assumed to be linearly dependent on their product \(u_{t}d_{t}\), that is
\[
e_{h,t} = au_{t}d_{t}, \text{ where } a \text{ is a constant to be calibrated.}
\]
This linear relationship carries the assumption that durables in the aggregate have a constant energy intensity.

Household’s problem

The household also derives utility from leisure, \(1 - h_{t}\). Its problem is therefore to maximize its expected lifetime utility
\[
E_{0} \sum_{t=0}^{\infty} \beta^{t} U(c_{t},h_{t})
\]
subject to the following budget constraint
\[
(1 + \tau_{e,c,t})p_{e,t}au_{t}d_{t} + (1 + \tau_{c,t})p_{n,t}n_{t} + (1 + \tau_{c,t})p_{d,t}i_{d,t} + p_{d,t}i_{k,t} + i_{B,t} = (1 - \tau_{i,t})(w_{t}h_{t} + r_{t}k_{t}) + R_{t}B_{t}
\]
where \(i_{d,t}\), \(i_{k,t}\) and \(i_{B,t}\) denote investments in durables, capital and government risk-free bond respectively, \(r_{t}\) the return on capital, \(w_{t}\) the wage and \(R_{t}\) the return on government bond. The household earns its income from the rental of its capital stock to firms, its labor service and the return on its government bond. The taxes it has to pay are: an ad-valorem tax on its energy consumption, income tax on its wage and return on capital, and consumption tax on its durables and non-durables consumptions.

Investment adjustment costs

Investments in capital and durables are subject to the following adjustment costs
\[
i_{d,t} = d_{t+1} - (1 - \delta_{d,t})d_{t} + \frac{\omega_{d1}}{1 + \omega_{d2}} \left(\frac{d_{t+1} - d_{t}}{d_{t}}\right)^{1+\omega_{d2}}
\]
\[
i_{k,t} = k_{t+1} - (1 - \delta_{k,t})k_{t} + \frac{\omega_{k1}}{1 + \omega_{k2}} \left(\frac{k_{t+1} - k_{t}}{k_{t}}\right)^{1+\omega_{k2}}
\]
Investment in government bond is also subject to a portfolio adjustment cost and is given by

\[ i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B_1}}{1 + \omega_{B_2}} (B_{t+1} - \bar{B})^{1+\omega_{B_2}} \] (5)

With \( \bar{B} \) calibrated it is then possible to solve for the aggregate price level in the economy.

**Depreciation rate of durables**

With the incorporation of variable utilization rate of durables it is fairly intuitive to also employ variable rate of depreciation of durables in this model. Naturally the depreciation rate should vary positively with utilization rate. Here we use a power-function form for the depreciation rate

\[ \delta_{d,t} = \frac{a_1}{a_2 + 1} u_t^{a_2+1} \] (6)

where \( a_1 \) and \( a_2 \) will be calibrated accordingly.

**Household’s optimal decisions**

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, which are 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’s 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, though should a need arise we can easily specify a different value of \( b \) for each sector. This parameter \( b \) is thus a technological parameter that embodies the energy intensity of capital or the degree of energy efficiency on the side of production. This specification allows us to look at how higher or lower energy efficiency impacts energy price, energy production and usage, and the overall economy.

Again it should be noted that energy does not enter the production functions directly; it is needed to enable the utilization of capital. The cost of energy shows up in the first-order conditions of the three producers, where it adds to cost of use of capital. The relationship \( e_{f,t} = bk_t \) implies a very high degree of complementarity between capital and energy; one simply cannot substitute away from energy unless capital itself is also substituted away. With this simple specification we emphasize the fundamental importance of energy in the operation of any kind of machines or infrastructures.
2.3 Energy Production

The energy sector, as in Huynh (2012), operates in a perfectly competitive market, and energy price is assumed to be fully flexible. The model implements an energy production with convex cost to bring about low price elasticity of energy supply.

The production function of the energy sector takes the form

\[ y_{e,t} = \exp \left( A_{e,t} k_{e,t}^{1-\gamma_e} \right) \]  

(7)

\[ A_{e,t} \] is the energy sector-specific productivity process

\[ A_{e,t} = \rho e A_{e,t-1} + \epsilon_e \]  

(8)

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

\[ b_{e,t} = \frac{\omega e_1}{(1 + \omega e_2)} (k_{e,t}^{1-\gamma_e})^{1+\omega e_2} \]  

(9)

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 details the process of calibrating this convex cost.

The firm’s maximization is

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

(10)

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

2.4 Durables and Non-durables Final Goods Producers

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

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

(11)

where \( \epsilon_i \) 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 good producer in sector \( i \).

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

\[ y_{i,j,t} = \left( \frac{p_{i,j,t}}{p_{i,t}} \right)^{-\epsilon_i} y_{i,t} \]  

(12)

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

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

(13)
2.5 Durables and Non-durables 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

$$y_{i,j,t} = \exp(A_t) (k_{i,j,t})^{\gamma_i} (h_{i,j,t})^{1-\gamma_i} - \chi_i$$  \hspace{1cm} (14)

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

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

$$A_t = \rho A_{t-1} + \epsilon_{A,t}$$  \hspace{1cm} (15)

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

$$\frac{\vartheta_i}{2} \left( \frac{p_{i,j,t}}{p_{i,j,t-1}} - 1 \right)^2 y_{i,t}$$  \hspace{1cm} (16)

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

$$E_0 \left\{ \sum_{t=0}^{\infty} \Lambda_{i,t} (p_{i,j,t} y_{i,j,t} - w_t h_{i,j,t} - (r_t + bp_{e,t}(1 + \tau_{e,f,t})) k_{i,j,t} - \frac{\vartheta_i}{2} \left( \frac{p_{i,j,t}}{p_{i,j,t-1}} - 1 \right)^2 p_{i,t} y_{i,t}) \right\}$$  \hspace{1cm} (17)

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 $i$

$$\hat{\pi}_{i,t} = \beta E_t[\hat{\pi}_{i,t+1}] + \frac{\epsilon_i - 1}{\vartheta_i} \hat{m}c_{i,t}$$  \hspace{1cm} (18)

where $\hat{\pi}_{i,t}$ denotes log-deviation of sector $i$’s inflation from its steady-state value, and $\hat{m}c_{i,t}$ 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

$$mc_{i,t} \exp(A_t)(1 - \gamma_i) \left( \frac{k_{i,t}}{h_{i,t}} \right)^{\gamma_i} = \frac{w_t}{p_{i,t}}$$  \hspace{1cm} (19)

together with sector $i$’s first-order condition resulting from cost minimization

$$\frac{1 - \gamma_i}{\gamma_i} \frac{k_{i,t}}{h_{i,t}} = \frac{w_t}{r_t + bp_{e,t}(1 + \tau_{e,f,t})}$$  \hspace{1cm} (20)

Wage and rate of return on capital are assumed to be equalized across all three sectors.
2.6 CPI Inflation

The CPI index for the economy is given by

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

(21)

And gross CPI inflation is thus

\[ \pi_t = \frac{p_t}{p_{t-1}} \]  

(22)

2.7 Fiscal and Monetary Policies

On the fiscal side the government levies three kinds of taxes: ad-valorem tax on energy consumption on both the household and the producers, consumption tax on durables and non-durables 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 payment on interest on the household’s current bond holdings.

Its budget constraint is given by

\[ \tau_{e,c,t}p_{e,t}a_{u,t}d_t + \tau_{e,f,t}p_{e,t}(b(k_{d,t} + k_{n,t}) + b_{e,t}k_{e,t}) + \tau_{c,t}(p_{n,t}n_t + p_{d,t}i_{d,t}) + \tau_{i,t}(r_{t}k_{t} + w_{t}h_{t}) + i_{B,t} = p_{t}g_{t}y_{t} + R_{t}B_{t} \]  

(23)

where \( g_t \) indicates government spending as a fraction of real output, and is given as an exogenous stochastic process.

Here we also assume that for its spending the government consumes a CES basket of durables and non-durables, similarly to the household, sans utilization rate for durables. Thus

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

(24)

such that

\[ p_{t}g_{t}y_{t} = p_{d,t}g_{d,t} + p_{n,t}g_{n,t} + p_{e,t}g_{e,t} \]  

(25)

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\(^4\)

\[ \log \left( \frac{\tau_{(t),t}}{\tau_{(0)}} \right) = \rho_{0}\log \left( \frac{\tau_{(t),t-1}}{\tau_{(0)}} \right) + \phi_{0}\log \left( \frac{B_{t}}{B} \right) \]  

(26)

where \( \tau_{(t),t} \) represents the general term for all four kinds of taxes in our model, with \( () = (e,t), (e,f), c, i, \) and \( \tau_{(0)} \) the corresponding steady-state rate for each tax. \( B \) is the steady-state value of nominal government debt.

\(^4\) These rules follow closely in form those of Forni, Monteforte and Sessa (2009).
The monetary authority sets the short-term nominal interest rate on risk-free bonds according to the following Taylor-type rule

\[ R_t - R^* = \alpha_R(R_{t-1} - R^*) + \alpha_\pi(\pi_t - \pi^*) + \alpha_y(y_t - y_{t-1}) + \epsilon_{r,t} \tag{27} \]

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

### 2.8 Aggregation and Equilibrium

Factor markets clear

\[ k_t = k_{d,t} + k_{n,t} + k_{e,t} \tag{28} \]
\[ h_t = h_{d,t} + h_{n,t} + h_{e,t} \tag{29} \]

as well as goods markets

\[ y_{d,t} = i_{d,t} + i_{e,t} + g_{d,t} + \frac{\varphi_d}{2}(\pi_{d,t} - 1)^2 y_{d,t} \tag{30} \]
\[ y_{n,t} = n_t + g_{n,t} + \frac{\varphi_n}{2}(\pi_{n,t} - 1)^2 y_{n,t} \tag{31} \]

With fixed costs ensuring that profits from the durables and non-durables sectors are zero in equilibrium, the budget constraint together with the two market clearing conditions above ensure that the energy market is cleared every period.

Aggregate output (value add) is defined as

\[ p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_{d,t} \tag{32} \]

### 2.9 Exogenous driving processes

The model is driven by four main shocks: the conventional TFP shock that is common to both the durables and non-durables sectors, a productivity shock that affects the energy sector alone, shock to government spending, and shock to the monetary policy function. An extension, for purpose of analysis, will also include shocks to the household’s energy consumption (shock to the parameter \( a \), and to the producers’ energy need (shock to parameter \( b \)).

Please refer to appendix A for the full set of equilibrium conditions of the model.

### 3 Model Calibration and Solution

The model is calibrated to the broad characteristics of U.S. economy at quarterly frequency. Table 1 displays the empirical ratios of main U.S. macro variables obtained from Dhawan and Jeske (2008)\(^5\) for the purpose of calibrating our model.

---

\(^5\) Dhawan and Jeske (2008), Table 1.
Certain standard parameters are calibrated following standard literature. The discount factor $\beta$ is set at 0.99, which translates to annual interest rate of around 4%. Following standard literature, the share of consumption in the household’s utility function $\varphi$ is set at 0.34, and the share of durables $\alpha$ in consumption is set at 0.2. Empirical research puts the elasticity of substitution between durables and non-durables close to 1. In this paper, the household’s utility function follows a general CES form, meaning that it cannot be used to model an elasticity of substitution of exactly 1. Here it is set at 0.99 for the main analyses, and the CES parameter of the household’s utility 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 possible the empirical moments found in aggregate US data.

Quarterly capital depreciation is calibrated at 1.5%, while the parameters of the durables depreciation function are chosen so as to produce a steady-state quarterly depreciation rate of 3.3% and utilization rate of around 80% for durables. Hence, $a_1 = 0.005, a_2 = 0.3$. The calibration of the parameters $a$ and $b$, the dependence of the amount of energy used on durables and capital respectively, is based approximately on the empirical ratios $E_h/Y$ and $E_f/Y$ in Table 1. The resulting calibration is: $a = 0.06, b = 0.012$.

The functional forms of capital and durables adjustments costs are given in the form of a general power function, governed by two parameters $\omega_1$ and $\omega_2$. In this paper we assume a quadratic form for both stocks, thus $\omega_{d1} = \omega_{k2} = 1$. The remaining choice of $\omega_1$ does not affect the steady state of the model, so it has to be chosen using the volatilities of capital and durables in the data as a guide. We used the following calibration, $\omega_{k1} = 50, \omega_{k2} = 1, \omega_{d1} = 5, \omega_{d2} = 1$.

The parameters of the three sectors’ production functions are also calibrated using the ratios in Table 1 as a guide, plus additional ratios such that the ratio of durables consumption to total real personal consumption. The capital share of the energy sector is also calibrated to be higher 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 to a great extent on the equilibrium dynamics of the system, meaning they are also carefully chosen so that 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’s and producers’ energy consumptions and energy output, and, of no less importance, by the equilibrium dynamics of the model. Parameter values that give 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 $\omega_{e2} = 2$. $\omega_{e1}$ is then calibrated to be 3.77, to give a price elasticity of energy supply of around 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 durables and non-durables sectors have their elasticity of substitution between their own varieties, $\epsilon_d$ and $\epsilon_n$, set at 5, a value frequently used in the literature, to give a steady-state flexible-price markup of 25%. The price adjustment cost parameters for durables and non-durables sectors, $\vartheta_d$ and $\vartheta_n$, 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 price in any given quarter is set at 0.75 to obtain a price contract length of about 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 $\theta = 0.75$, while that in the Phillips curve derived here is $\frac{\epsilon_d - 1}{\vartheta_d}$. Equating these two thus gives us $\vartheta_d = \vartheta_n = 46$, meaning that for the baseline analysis the prices of two sectors are considered to be equally sticky.

Ad-valorem energy taxes are calibrated to be 10% at the steady-state, while income tax is 15%, and consumption tax 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), also used in Leduc and Sill (2004), and set: $\alpha_R = 0.8$, $\alpha_\pi = 0.2$, 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 $\phi_{e,c} = \phi_{e,f} = \phi_c = \phi_i = 0.12$.

The full set of equilibrium conditions is provided in appendix A. 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.

4 Baseline Taylor Rule Calibration

In this section we take a quick look at how the economy responds to different supply and demand shocks, with the monetary policy function calibrated to a standard Taylor-type rule as outlined in section 3. We make the comparison of this baseline rule with a more ‘passive’ interest-peg regime. The four shocks follow those of Huynh (2012) and are the focus of analysis throughout this paper: a negative productivity shock to the energy sector, a positive TFP shock to the non-energy sectors, and two positive energy-market specific demand shocks, coming from the household and the producers respectively.

Figures 1 to 4 show the responses of output to the four shocks considered in this paper under the two different regimes. The energy supply shock is calibrated to produce a 10% increase in energy price. The TFP shock to the non-energy sectors is equal to the standard deviation of the shock process, 0.007. The energy-market specific demand shock coming from the household is caused by a 10% increase in the value of $a$, the energy intensity of durables, while the energy-market specific demand shock coming from the producers is caused by a 10% increase in $b$, the energy intensity of capital.
The demand shock to the household’s energy use causes energy price to increase by 14%, and the demand shock to the producers’ energy use cause energy price to increase by close to 26%. Similar to the results in Huynh (2012), the energy price elasticity of output goes progressively greater in magnitude from the energy supply shock to the demand shock through $a$ to the demand shock through $b$. Energy price increases have an adverse effect on the business cycles for these three shocks. Output, consumption and investments shrink, and inflation rises. In the case of an energy supply shock aggregate demand and supply are shifted leftwards because of lower supply in energy, while the same effect is achieved through a higher demand/consumption of energy in the case of the two demand shocks to the energy market. The TFP shock on the other hand engenders an energy price increase of around 1.5% through the expanding business cycles, and the relationship between output and energy price for this shock is a positive one. The TFP shock causes the price level to drop, in line with standard literature, therefore the co-movement between energy price (to be more precise, the real price of energy) and inflation is also opposite to that in the other three shocks. The broader and indirect nature of this shock on the energy market means that the increase in the relative price of energy is a lot smaller than the increase encountered in the other three instances of energy price increase.

Overall the response of the business cycles to these shocks follows closely Huynh (2012), in which extensive analyses were made on the distinct effects of each shock.

5 Monetary Shocks and Energy Prices

With endogenous energy production we have opened up a channel that links demand back to energy production and price, and this could prove to be an important one with regards to our analyses of monetary policies. This feedback channel allows changes in monetary policy to have an impact on energy prices. As monetary policy changes could have an expansionary or contracting effect on aggregate demand, it is expected that energy price would either rise or fall with it. It is therefore important to have an energy supply that is fairly price inelastic, to render meaningful any changes in energy price through changes in aggregate demand.

In this section we investigate this link. We cause a shock to the nominal interest rate to raise it by 20 basis points (annualized), and observe the effects of this shock on output and energy price under a variety of monetary regimes. By doing this we shed light not only on how monetary policy changes raise or lower energy prices but also on the different dynamics of energy prices under different monetary regimes.

Figures 5 to 10 display the surface plots of output and energy prices as the weight on inflation goes from 0 to 0.4, at three weights on output: 0, 0.15, and 0.3.

As expected, an unexpected increase in the nominal interest rate contracts consumption, investment and output. Energy price falls as a result, as well as the price level. It is also important to note that it is the real price of energy relative to the non-durables goods that falls, as the general price level drops to a much smaller extent. This reflects a smaller demand for energy good. The demand-side impact of this shock on energy price and production is very clear given the tight correlation between the
responses of energy price, energy output and aggregate output (value add). Larger fall in output is associated with larger falls in energy output and energy price. We can therefore view the impact of this monetary shock on the energy market in similar ways to a TFP shock: an aggregate shock that has an indirect impact on the demand side of the energy market. The distinction with a TFP shock is clear in the positive relationship in this case between inflation and the real price of energy. It shares with the TFP shock however the positive movement between output and the real price of energy. We also see that different interest rate rules lead to a variation in the degree and persistence of energy price increases, since these rules trace out diverse interest rate paths in response to this shock and so determine differently how aggregate demand recovers from this shock. Strong focus on inflation produces smaller falls in output and energy price. Targeting output strongly without a correspondingly hawkish attention on inflation, on the other hand, only ends up causing larger contraction in the business cycles and larger fall in energy price. The responses of energy price, output and inflation also get more volatile the larger the weight on output, when the focus on inflation is not large enough.

As interest rate shock is by origin a nominal disturbance - though with consequences on the real side of the economy and indirect impact on energy prices - it is expected that price stability is an effective goal, with or without accompanying focus on output. Also, since both output and inflation fall in response to this shock, a focus on inflation would coincide with focus on output: both call for a stimulation of aggregate demand.

The main lesson learned here is that monetary changes and the accompanying monetary regime play an active role, even if small, in determining the responses of energy price and production.

6 The Role of Monetary Policy

6.1 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. In this, the contributions of Bernanke, Gertler and Watson (1997) are well known, though the validity of their conclusion was challenged by Hamilton and Herrera (2004). Kormilitsina (2011) and Leduc and Sill (2004) also arrived at different conclusions on what the optimal monetary policy would be, given their different approach at defining what is optimal for the economy. Bodenstein et al (2008) and Nakov and Pescatori (2010) incorporated features of endogenous energy price into their frameworks and also arrived differently at the optimal monetary policy response to an energy price 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. Our approach to evaluating the various monetary policies is similar to that of Leduc and Sill (2004), by focusing on the responses of the observable macro variables such as output and consumption. We calibrated the shock to the productivity of the energy sector so as to produce a 10% increase in
energy price. This is a temporary shock that creates a half-life for the energy price increase of about 12 quarters. Figures 11 to 19 show on surface plots the responses of output, inflation and interest rate when the inflation coefficient of the Taylor rule is swept from 0 to 0.4 while the output coefficient is fixed at three values: 0, 0.15 and 0.3.

One main observation jumps out when the monetary policy function pays no attention to variations in output in response to this shock. As more emphasis is placed on fighting inflation, the response of output gets progressively worse, even though the objective of obtaining smoother, less volatile response in inflation is achieved. The maximum drop in output goes from around -0.7% with an interest rate-peg regime (nominal interest rate is fixed at steady state value) to -1.1% with a maximum response on inflation. The aggravation of this regime is therefore very large, almost a 60% larger drop in output for a 10% increase in energy price. It is also noted that when the weight on inflation is sufficiently large, it causes a straight drop in output upon the shock’s impact rather than a trough response.

As more weight is put on responding to output fluctuations, the drop in output gets smaller, while inflation gets higher. However, at the two higher values of output coefficients (0.15 and 0.3), as the inflation coefficient gets higher, inflation response does get smoother as well; the interest rate path also displays considerably less fluctuation. A larger weight on inflation helps manage expectations of inflation, and so keeps interest rate from changing too rapidly from one period to the next.

Responding to output alone however doesn’t seem to be effective either, by comparing the outer edge of each output surface plot (where inflation coefficient = 0). As the rule gets more aggressive at fighting output fluctuations, with no or little regard to inflation, it actually causes larger contraction and more volatile response in output.

The best response in terms of output is achieved when the monetary rule is aggressive at both responding to output fluctuations and managing inflation expectations. That happens when the weight on output is maximum at 0.3 and the weight on inflation is quite high at around 0.3 as well. The path of nominal interest rate shows that the monetary authority is required to bring it down gradually and keep it steady before slowly raising it back to steady state. Inflation is initially accommodated and is the highest at more than 0.15% at this point. The policy also does quite well at maximum weights for both output and inflation, with similar interest rate path.

The response of household’s consumption and investments follows closely that of output. Consumption and investments shrink as a consequence of the shock, but smaller drops in output lead to smaller drops in these variables as well.

Furthermore, Figures 20, 21 and 22 display the variances of output, inflation and consumption achieved under different monetary responses. A few observations are in order. With a strong focus in inflation, we achieve less volatility in inflation but have to trade that off with higher volatility in output and consumption. A policy that is aggressive in fighting with both inflation and output fluctuations seems to give us the best trade-off between the volatilities of all three variables. In addition, an interest rate-peg regime does fairly well compared to more aggressive policies in terms of keep-
ing the three volatilities reasonably low.

Therefore, even though the best performing in terms of minimizing output and consumption contractions is one that has a balanced weight between inflation and output stabilization, the realized path of the interest rate indicates that the monetary policy should lean towards stabilizing output. In this event of adverse shock to the economy, this means stimulating output by reducing the nominal interest rate. Indeed, the penalty in terms of more severe drops in output and consumption for a more heavy output-stabilizing policy is smaller than a strong inflation-fighting one.

This caution against fighting either inflation or output too strongly without due attention to the other mandate is also told in the surface plots of the nominal interest rates. The harm to output and consumption is greatest when the nominal interest rate responds to the shock with an immediate jump, meaning the monetary policy following a strict price stability mandate. The drops in output and consumptions are also large when the nominal interest rate drops immediately after the shock, as in following strict output stabilization mandate. The best policy, as shown, occurs when the interest rate is adjusted gradually, making an initial accommodation for inflation, 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 gets greater, the interest rate slowly tightens up again to reach back the steady state eventually.

The responses of the economy to this wide range of monetary regimes are first to be understood by looking at the source of the energy price shocks. 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 naturally pushed up. Aggregate supply shrinks as a consequence. The presence of nominal price rigidities means that the non-energy producers are even more sluggish to adjust 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. Since the household is also affected by the negative income effect due to higher energy price, aggregate demand also shifts leftward. Thus this energy price hike is a result of both demand and supply shrinking.

A strict price stability regime is forced to raise interest rate right after the shock hits because of the hike in inflation. The goal is to counter the rise in real marginal costs of production. And yet, because a large part of this upward pressure on the marginal costs is due to the surge in the real price of energy, a desirable reduction in real marginal costs can only come about by engineering a real reduction in energy price relative to the other prices. This course of action - fighting inflation aggressively - turns out to be too broad and too aggressive. It tries to engender a reduction in the relative price of energy indirectly through deflating the non-energy goods by contracting aggregate demand to raise the producers’ marginal products of capital and labor (as we have seen in section 5, contracting aggregate demand through a restrictive interest rate regime could bring down the relative price of energy). But its effect on real energy price relative to the broad impact it has on aggregate demand (and output) is too small compared to what is needed for this scenario to be successful. So what happens instead is only slightly lower real price of energy, traded off with a large
additional depression of output. Higher interest rate also triggers a flight from capital that worsens the fall in the capital stock compared to less aggressive inflation-fighting stance. The consequence of a strict inflation-fighting regime is thus an exacerbation of the negative effects of the shock. It is evidenced by the observation that when the weight on inflation is at its highest value the real marginal costs of the producers actually decrease in response to the shock despite the cost-push effect of higher energy price. This tells us is that the pressure imposed on the producers by higher costs of energy is outweighed by the fall in demand so much that their marginal costs drop.

Given the broad impact of changing the nominal interest rate, the answer is 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. But as demand is forced to shift back to the right, the drop in output and consumption is lessened. The trade-off between the impact on output and the impact on real energy price is precisely the opposite of a restrictive monetary stance. The real price of energy rises slightly higher, but the benefit on output and consumption outweighs that. Additionally, lower nominal interest rates stimulates investment in capital, allowing the economy to maintain a higher stock of capital that is beneficial over the longer run, compared to a very strict inflation-fighting regime. Paying sole intention to variations in output, however, results in too large an immediate drop in interest rate. This, as opposed to a strict inflation mandate, means an excessive stimulus to aggregate demand. This may result in a smaller initial drop in output, but since the nominal interest rate is dropped too low too quickly, this causes an excessive building up of capital that pushes down the real return to capital. In the subsequent periods this sees the household getting squeezed further in their income by the already low return on government bonds and the collapsing return on capital. The result is a further fall in output and consumption as aggregate demand shifts to the left even more. With a sole, strong focus on output, the monetary policy is forced to bring down the nominal interest rate further, aggravating the contraction in output and consumption. The responses of inflation reinforce this notion (by looking at the outer edge of each surface plot of inflation). As the weight on output gets larger, prices go through a period of deflation after the initial inflationary duration. The stronger the weight, the worse the deflation gets. The inefficiency of boosting up output too much shows itself a few quarters later after the shock.

The prerogative therefore is a balance between the initial impact and the subsequent influence on aggregate demand (both in terms of consumption and investments) of the inter-temporal effects of changing interest rate. Strict price stability raises interest rate too high too quickly when the economy is in need for stimulus. Output recovers straight from the initial drop, as the leftward momentum of aggregate demand is checked and reversed, but this initial loss in output (and consumption) is too great. The overall loss from this is still larger than the case of a more balanced policy approach. Conversely, strict output focus drops interest rate too low too quickly. The excessive stimulus drags output up but inadvertently reinforces the contracting momentum of aggregate demand as too much future wealth is sacrificed. The result is more harm on the economy a few quarters down the road. The dual mandate therefore ensures an interest rate path that does not cause output and consumption to deviate too much either way.
Our results deviate strongly from those of Leduc and Sill (2004), even though we both assess the performances of systematic monetary policy from the view of its impact on output. Leduc and Sill (2004) called for price stability as the weapon of choice against such shocks. A dovish policy, they argued, would initially require keeping interest rate low to boost output, but as that would raise current and expected inflations, given that the monetary policy also cares about fighting inflation, interest rate ends up getting higher and so output drops deeper. Our results do in fact point out that placing too much emphasis on output and too little on inflation would actually cause much fluctuation in interest rate and even more contraction in output. And so we are indeed in agreement with Leduc and Sill (2004) that if we put a high weight on output, it is better to accompany that with a strong attention on inflation as well. However, our central point remains distinct from theirs from this point onwards. Leduc and Sill (2004) showed that a strong weight on inflation with low focus on output is better, since according to their analyses increasing weights on output always amplifies the negative impact of the shock on output while increasing weights on inflation always does the opposite, regardless of the weight on the other coefficient. Our framework on the contrary has shown that increasing weights on inflation does not lead to lower output contraction at every level of output weight, only in cases where the weight on output gets sufficiently high, and that increasing weights on output does not always lead to more severe contraction in output at every value of the inflation coefficient. For us, consequentially, a hawkish stance on inflation should not be without 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. The main source of distortion comes from the sluggishness of the non-oil producers to adjust their prices to keep up with this higher nominal cost. As Nakov and Pescatori (2010) stated, such 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 results therefore tell us to interpret differently the desirable response of the monetary authority in terms of minimizing impacts on output and consumption. The emphasis should be leaning towards stabilizing output, with an appropriately high level of price stabilization to avoid providing excessive stimulus and inadvertently causing more volatile responses of output and consumption (and of most other macro indicators). Nevertheless, our results do agree with Leduc and Sill (2004) in another aspect: the recessionary impact of energy price shocks due to an energy supply shock would be less if the nominal interest rate is kept constant rather than follows a baseline Taylor rule.

Our findings are more in line with Bodenstein et al (2008), which 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, like theirs, lean towards output stabilization. However, our findings do not advocate moving away from a balanced approach towards too much output stabilization. As explained above, this leads to excessive stimulus and amplifies the subsequent responses of most of the macro variables. Indeed the variation in the response of the business cycles can be quite considerable when we move across different weights on output stabilization. This is contrary to findings from Bodenstein et al (2008) that
the performances of the economy across a wide range of output stabilization are close to indistinguishable. Our framework therefore indicates a higher sensitivity to output stabilization and stresses on a careful consideration of how much focus to put on stabilizing output.

Nakov and Pescatori (2010), though also using welfare as the criterion for evaluation of alternative monetary regimes, did not come to similar conclusions to Bodenstein et al (2008). They did stress that a strict price stability regime deviates from an optimal policy, but did not go as far towards output stabilization. Their distinction with 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 a more aggressive inflation-fighting policy or a strict inflation targeting policy. They also found that an interest rate peg regime is the worse of the lot, not just in terms of welfare but also in terms of inflation and output contraction and volatility. Our analyses in terms of drops in output, consumption and welfare simply say the opposite on both of these points. Also, the interest rate peg regime in our model does not lead to more volatility in inflation and output compared to other alternative regimes. 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 interest rate as if fighting inflation, and if it is not accompanied by any focus on output, then it might simply mean an excessive focus on price stability, a stance that our results do not advocate. Despite these differences, the overall recipe from Nakov and Pescatori (2010) for a simple targeting rule in terms of welfare is a flexible inflation regime, with a weight on output gap half that on inflation. They call for a degree of stimulation for the economy when oil price is high, which has a lot of similarity with what we consider to be the best performing policy in terms of output in our analyses.

With regard to Kormilitsina (2011), our results agree only in the response of inflation, that it should be let to rise. However the reasons behind this are very different between our results and those of Kormilitsina (2011), and consequently the desired path of nominal interest rate also differs between the two results. In her framework, the nominal interest rate has to rise to accommodate a rise in the real interest rate, considered optimal in the point of view of the Ramsey planner. For us, high inflation is achieved because of a lowering of interest rate by the monetary authority, to accommodate inflation and boost output. This difference is traced back to the response of real interest rate to energy price increase. In the RBC version of her model, the real interest rate rises, but the results from our RBC version (where the return rate of capital represents the real interest rate) indicate that it must drop due to the downward pressure of high energy price on the marginal cost of capital. Therefore, in our New Keynesian framework, it is in fact more desirable for the real return rate of capital to drop as well. Raising the nominal interest rate too high to induce an increase in its real rate would put an upward pressure on the real rate of capital, as the household moves away from capital investment (more than is dictated by the adverse energy price shock), and the supply of capital is reduced more than is efficient.

Nonetheless, Kormilitsina (2011) also proposes from the view of Ramsey-optimal policy that a policy paying less attention to inflation would come close to the optimal policy, which does not go against our analyses, but her prescription of higher nominal
interest rate leaves it without much detail on the more precise nature of a desirable simple targeting or Taylor-based rule. Our results thus go further by indicating a primary focus on output, initial inflation accommodation and a balanced attention on inflation so as to achieve more stable paths for both inflation and output.

6.2 TPF shock to non-energy producers

The picture is different for the case of positive productivity shock to the non-energy sectors. A supply shock in this manner could cause energy price to increase even though it would lead to a drop in non-energy prices and the general price level. This reflects a broad, indirect demand shock to the energy market as the household consumes and invests more in durables and the producers uses more capital in production.

Figures 23 to 31 display the surface plots of output, inflation and nominal interest rate for three weights of output (0, 0.15, 0.3) as the weight of inflation goes from 0 to 0.4. For this shock, aggressively responding to inflation/deflation seems to be the most effective way to accommodate the expanding business cycles, in ensuring highest rise in output and consumption. As more weight is put on output, output expansion is curbed right after the shock and rises to a lower peak. Also, in this scenario, an interest rate-peg regime does just as well as a regime designed to respond aggressively to both inflation and output. Again, responding solely to output results in higher volatility in output, inflation and interest rate.

The main distinction from the case of energy supply shock comes from the co-movements between output and energy price and between inflation and energy price. The economy benefits from a rightward shift in aggregate supply. Therefore an effective way to respond is to slowly bring aggregate demand up to catch up. An inflation-focused monetary objective in this case serves that purpose. This causes energy price to rise higher. But since an expansionary monetary stance engineers a reverse co-movement between inflation and the real price of energy (as we have seen from section 5), what we end up with as we fight deflation more aggressively is a smaller degree of deflation to accompany a slightly higher nominal energy price. The negative effects of a real energy price increase are therefore not much greater. Focusing only on output means a rise in interest rate to put a brake on the expansion. It has the immediate effect of dampening consumption and investment. This is shown in the deeper drops in real marginal costs, as the producers have to balance increased productivity with a slower-growing demand. But this also means that the household is transferring its current consumption to the future as the household seeks to transfer their consumption to bonds. This comes at a time when higher productivity is putting pressure on output, and consequently household’s income, to grow. This pressure is instead transferred into excess bond holdings. After the inter-temporal effects of increasing interest rate have been in play for a few quarters, they start to bring higher income to the household. So as the momentum of a supply increase slows down, demand starts its own upward momentum. We can see that at higher weights on output, deflation is reversed into inflation near the 4th quarter mark. However, the effects of higher interest rate also include lower investment in capital. This means that 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. Figure 32 makes
this clear, as it compares the capital stock between a strong price stability regime and a strong output stabilization regime. As a consequence, even though output continues to rise until after the 5th quarter, its peak is of a smaller magnitude compared to when the focus is put instead on inflation. Thus, higher weights on output cause larger dampening of demand at the start but greater demand momentum later that result in high volatility in output and inflation, but they also mean that a chunk of potential output growth is taken away because of an inefficient build-up of capital. The response of consumption very much follows the behavior of output. Responding strongly to inflation and output at the same time is better than a sole focus on output in the sense that the response of the economy is less volatile, but output growth is also curbed, because interest rate rises back up too quickly with the monetary authority overly concerned with stabilizing output.

A prescription for the monetary policy thus calls for a strong take on inflation. This has the immediate effect of releasing most of the deflationary pressure as it allows demand to shift quickly to meet the increase in supply. What we have consequentially is smoother responses for all the macro variables. Output rises fully to its maximum and declines as the productivity shock wears off. Interest rate is kept slightly lower than steady state for a long period to sustain the productivity increase, and prices are thus allowed to slowly decline over the period of higher productivity.

The results of 6.1 and 6.2 can be distilled further into the observation that in both cases, there is no question of responding positively to energy price increase in terms of monetary policy, whether energy price is a good indicator for inflation or output in each case. They also highlight the crucial consideration that is a common theme in dealing with instances of energy price shocks: the trade-off between engineering a reduction in the relative price of energy and minimizing the impact on output and consumption. Viewed in another way, it also means a balance between the immediate effect on aggregate demand of a monetary response and its longer-term, inter-temporal impact, especially on capital. Though the main guiding principles are the same, each shock merits a clear, thorough look at its nature, and each instance of energy price increase needs to be looked at for its underlying cause, so as to arrive at the right trade-off point.

### 6.3 Energy-market Specific Demand Shocks

The endogenous energy production and convex costs allow us to analyze the impact of demand shocks to the energy market on the economy, as they create a mechanism for large energy price responses and much less responsive energy supply, a stylized fact about energy observed in data. In the context of a theoretical model, a high price elasticity of energy supply would certainly make analyzing any shock to the demand side of the energy market a lot less meaningful, since the resultant energy price increase would be too small to cause much impact.

The two energy-market specific demand shocks analyzed in this paper are identical to those studied in Huynh (2012). One is a shock to the household’s energy intensity of durables, represented by the parameter $a$, the other is a shock to the producers’ energy intensity of capital, represented by the parameter $b$. Any increase in the value
of either of these two parameters means in surge in demand for energy for a given stock of durables or capital, but one comes from the household’s side while the other comes from the production side. As already stated in section 4, these shocks cause large increases in energy price and carry significant recessionary implications for the economy. The purpose here is to see if and how the monetary authority is required to respond differently to these shocks.

Figures 33 to 38 display the surface plots of output in response to the two shocks for three weights of output (0, 0.15, 0.3) as the weight of inflation goes from 0 to 0.4. Qualitatively these two shocks call for similar policy response to the case of energy supply shock. Even though they are technically demand shocks, and they do raise energy demand/consumption in the economy, their overall effect on aggregate demand is actually contractionary due to the large negative income effect that higher energy prices have on durables and non-durables consumption (supply shifts to the left as always due to energy being an input into production). So 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, to let inflation rise at the start, while at the same time having a tight rein on inflation to avoid excess stimulation and high volatility in the responses of the aggregates.

What distinguishes these two shocks from the usual case of energy supply crunch is the greater elasticity (in magnitude) of output (value add) to energy price. The relative extent of the impact of 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 on the business cycles in response to these shocks, especially from the demand side. The surface plots of output show clearly that within the same range of values for the weights on output and inflation, the monetary policy response does not bring the same benefits (or cause the same extent of damage) to output (and also consumption) in these two shocks. The negative effect of focusing solely on price stability is worse for the case of an increase in $a$. The clue to understanding this is shown in Figures 39 and 40 with the observation that for the shock to $b$, the maximum focus on inflation brings about a fairly larger reduction in inflation. Inflation caused by an interest rate-peg regime in the case of the shock to $a$ is lower, but ironically the effectiveness of a strong inflation-fighting regime is also lower. The fact that a strong inflation-focus monetary objective causes output to drop relatively more but inflation to drop relatively less in the case of an increase in $a$ tells us that aggregate output is more adversely affected by this high interest rate regime when it is used in response to the energy demand shock coming from the household.

The rationale is as follows. For both shocks, inflation occurs when both supply and demand have shrunk, the inflationary cost-push effect overcoming the deflationary income effect. But since the demand shock coming from the increase in household’s energy intensity of durables has a disproportionately larger impact on aggregate demand, this means the increase in $a$ has already shifted aggregate demand by a relatively larger extent than the increase in $b$. This is evidenced by the greater elasticities (in
magnitude) of durables investment and overall consumption to energy price in the case of the shock to $a$. A strong inflation-fighting monetary response would shift demand further to the left. But in the case of demand shock coming from $a$, the household’s consumption has moved to a point of very high marginal cost for any further marginal reduction in durables investment, and so the substitution effect ensures that the household doesn’t reduce its durables stock much further when the nominal interest rate gets higher, but turns to cutting more of its capital stock. Figures 41 and 42 illustrate this point by showing a comparatively greater downward movement of capital investment between the minimum and maximum weights on inflation in the case of shock to $a$. This would mean that there is immediately a disproportionately tighter squeeze on capital for production in this case compared to the shock to $b$. The consequence is that, for the case when the demand shock to the energy market comes from the household, supply is adversely impacted by a larger extent, causing a stronger inflationary pressure on prices, and so a strong inflation-fighting monetary response is comparatively less successful at bring down inflation.

It is of no surprise too then that the benefit of aggressively fighting both inflation and output is smaller for the demand shock coming from $a$. As Figures 43 and 44 show, at maximum values for both inflation and output coefficients, the aggressive dual-mandate monetary regime achieves a 16.7% reduction in initial drop of output for the case of increase in $a$ vs. a 40% reduction for the case of increase in $b$, relative to an interest rate-peg regime. The improvement in terms of maximum output contraction is better for the case of $b$ as well, in percentage terms. A similarly aggressive regime also delivers better improvement in both of these measures for the case of energy supply shock. The reason is the presence of an amplification mechanism from the demand side for the case of energy demand shock through $a$. When the household’s durable stock is more energy-intensive, the impact of the demand shock goes beyond energy price itself, as the increased cost of durables investment and utilization is reflected by more than just energy price. The elasticities of household’s consumption and investment (with the exception of capital investment) to energy price in this case are greater in magnitude than both the cases of energy supply shock and demand shock through $b$. This greater pressure on durables consumption causes the expansionary monetary regime to be less effective at bringing up demand to minimize the contraction in output. The demand shock coming from higher energy-intensity of capital on the other hand causes a much greater elasticity (in magnitude) of capital investment to energy price, since the increase in energy cost for producers is by more than just the energy price increase. The shock thus has a disproportionately greater impact on the supply side of the economy. A strong inflation-regime triggers the substitution effect from the household in precisely the opposite direction between capital and durables investments. An output-stabilization regime is therefore able to stimulate demand to a greater extent, since the amplification mechanism of higher energy demand from the household is absent.

Both of these shocks, however, cause greater sensitivity of inflation response to energy price increase than the energy supply shock, if viewed under the interest rate-peg regime. Given that these two shocks also cause output (value add) to have greater elasticity (in magnitude) to energy price, this means there is a larger inflationary pressure on prices coming from the supply side of the economy. This is immediately
apparent in the case of demand shock through $b$, as the cost-push effect of high energy price is a lot larger for this case, since the increase in energy cost for the producers is the combination of high energy price and higher energy-intensity of capital. But surprisingly this effect is also greater for the demand shock coming from $a$, compared to the energy supply shock. This comes directly from the different natures of these two shocks. Both (and the demand shock through $b$) are adverse shocks that reduce the capital stock in the economy; at the same time they cause more capital to flow into the energy sector. This relocation of resources is more massive for the case of demand shock through $a$ (and $b$), because the energy sector has to cope with an increase in demand for its good. This has the immediate effect of squeezing even more the capital allocations to the non-energy sectors. The pressure on the producers to raise prices is therefore disproportionately larger.

The two demand shocks to the energy market show important quantitative differences in their impact on the business cycles as well as in their interactions with monetary responses. These distinctions come from the different degrees of impact on the demand and supply sides of the economy and the diverse relocations of resources in accordance with the sources of the shocks. The effectiveness of monetary intervention definitely varies between the two shocks, and the need here is to be mindful of this fact so as to not go too little or too far in devising the appropriate responses.

7 Sectoral Dynamics

7.1 Sectoral Inflation

Figures 45 to 48 display the response of durables and non-durables prices to the four shocks analyzed in this paper under the interest rate-peg regime.

The three adverse shocks cause the non-durables sector to experience higher inflation, while in response to the TFP shock to non-energy producers there is little difference between the movements of non-energy prices. This tells us that in the case of the three adverse energy price shocks, their relative impact on the durables and non-durables sectors is rather different. In the non-durables sector there is greater upward pressure on its prices, even though both sectors are subjected to the same increase in the cost of energy price. The difference in the impact comes rather from the demand side of each sector. As the consumption of goods from the durables sector is energy-dependent, the increase of energy price makes its goods more expensive to the household, triggering a substitution effect that moves the household towards less energy-dependent goods. The negative impact on the demand side of the durables sector is thus due to more than just the general negative income effect that also affects the non-durables sector, and is therefore disproportionately greater. The non-durables on the other hand benefits from this substitution effect, which alleviates to a certain extent the fall in the demand for its goods. Thus, for the non-durables sector, a shrinking supply and a less shrinking demand see a higher upward pressure on its real marginal costs. This also means that eventually non-durables prices settle at a higher peak than durables prices. Viewed another way, this inter-sectoral dynamics reflects the fact that in adverse energy price shocks, non-durables become more valuable to the household.
The TFP shock to the two non-energy sectors on the other hand increases the relative price of energy by a more aggregate force of the expanding business cycles, which increases household’s income. The energy sector benefits from the general rise in consumption, part of which needs energy. The substitution effect plays little role in this shock, because even though the relative of energy increases, the magnitude of its increase is a lot smaller, due to the aggregate nature of the shock to its demand. Another kind of shock, such as a monetary shock, which also has an aggregate impact on the energy market, also causes the prices of the two sectors to move pretty much close to each other (Figure not shown here).

The size of the inflation differential in each shock also provides us with an insight into the nature of the shock. From the TFP shock, where the two prices’ movements virtually coincide with each other, the relative increase in the price of energy is too small to trigger any meaningfully large substitution effect. For the other three adverse energy price shocks, the differential is smallest in the case of the energy demand shock coming from the producers, and is largest in the case of the energy demand shock coming from the household. We learn from this the extent of each shock’s impact on the durables’ demand relative to non-durables’ demand. In the case of an increase in \( a \), the negative income effect comes from more than just the hike in energy price, the downward pressure on demand of durables is therefore disproportionately greater than either the case of energy supply shock or the increase in \( b \). This has the effect of widening the inflation differential between the two non-energy prices, as there is more inflationary pressure on non-durables prices, and less of such pressure on durables prices correspondingly.

### 7.2 Sectoral Price Rigidities

In the baseline calibration of the model, both 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 cycles to each of these price rigidities in events of energy price shocks. Gaining an understanding of this would give us an insight into how energy price interacts with the price sluggishness of various goods and the combined influence of a good’s energy-dependency and its price stickiness on the overall impact of an energy price shock.

For analysis we ran the model along a two-dimensional grid containing values of price rigidities of the durables and non-durables sector. Throughout this exercise the monetary policy function is kept at the baseline Taylor-type specification as in section 4.

Figures 49 and 51 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 durables: more flexible \((\vartheta_n = 1)\), as sticky \((\vartheta_n = 46)\), and more sticky \((\vartheta_n = 86)\), while Figures 50 to 52 show the output responses to these two shocks at three degrees of durables price rigidity relative to non-durables: more flexible \((\vartheta_d = 1)\), as sticky \((\vartheta_d = 46)\), and more sticky \((\vartheta_d = 86)\).
First it is important to make the observation that as price rigidities get lower the impact on output and consumption is greater for these two shocks. And the same is true for the two energy-market specific demand shocks as well. As energy price increases, the non-energy producers’ output shrinks. A sector’s price rigidity determines how quickly it can reset its prices upward to adjust to higher costs of production. Lower price sluggish lets a sector to revise its prices higher quickly, allowing it to reach a lower level of output as its optimal production point. Therefore, when prices in a sector are more flexible, the contraction in output in that sector is larger. The substitution effect in fact ensures that the contraction in the other sector is lessened, but this improvement is never enough to cause value add to drop less. Similar reasoning applies for the case of TFP shock to the non-energy producers.

From the graphs it is clear that the price rigidity of the durables sector plays a greater role in determining the responses of the economy. Output (value add) has a higher sensitivity to variation in this price rigidity. The main reason is again that in energy price shocks, especially the adverse ones, the durables sector’s response is always more volatile due to the bigger impact of the shocks on its demand. The nondurables become like a kind of ‘anchor’ goods in these adverse times, and so its consumption shows a lot lower sensitivity than durables (and capital) consumption to energy price. Another reason is that the behavior of the non-durables sector shows higher sensitivity to variations in the durables’ price rigidity than vice versa.

Thus, as non-durables prices get more flexible, the contraction in nondurables output gets more severe. But this contraction is already of quite small a magnitude, in the order of 0.3 to 0.4% for a 10% increase in energy price. At the same time, the fall in durables output is in fact lessened (due to the substitution effect), but this change is negligible. The result is that the variation in the response of value add is within the 0.1 - 0.2% margin as seen in Figure 49. Conversely, as durables prices get more flexible, the contraction in durables output gets worse, and the variation can be up to the order of 1%. Non-durables output displays noticeable sensitivity too. Its output drop lessens at more flexible durables prices, but this is of a small magnitude and does little to alleviate the considerable worsening in durables output contraction.

As a consequence, value add displays noticeably higher variation within the same range of durables price rigidity, Figure 50. 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-dependency among these goods. As energy price gets higher, it triggers a substitution effect that moves the household from more energy-dependent goods towards less energy-dependent goods, balanced of course by the income effect. Consumption of durables moves much more strongly than the consumption of non-durables. So upon the impact of energy price shocks, the household moves to a point of consumption where the marginal utility of durables consumption is already a lot higher than that of non-durables consumption. When prices of more energy-dependent goods are more flexible, meaning the initial surge in their prices is higher, this reinforces the move towards less energy-consuming goods, but this also requires the household to acquire a relatively large quantity of non-durables for a small marginal reduction in durables consumption. Non-durables consumption is therefore highly sensitive to the price stickiness of durables. And conversely, when prices of
non-durables are more flexible, the move back towards durables consumption simply doesn’t happen 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 durables consumption. Hence durables consumption and output simply do not exhibit the same sensitivity to nondurables’ price rigidity.

However, it is important to note that the above analysis should apply only to instances of energy price shocks where the increase in the relative price of energy is high, and the source of the shock is more confined to the energy sector. Varying price rigidities in the durables and non-durables sectors in this case do not cause the magnitude of energy increase to vary in any significant way. More aggregate shocks such as the TFP shock and monetary shock, on the other hand, cause the relative price of energy to rise a lot less, and the secondary nature of the energy price increase means that changes in the degree of price stickiness in either sector can lead to significantly different responses of energy price. With the reverse causal relationship between energy price and energy demand being much stronger, it is then very difficult to establish the degree of influence of each good’s price rigidity.

8 Conclusion

This paper introduces New Keynesian features into the RBC framework of Huynh (2012) to extend the analysis on the role of monetary policies in the event of shocks to the energy market. This is done in the context of endogenous energy production, allowing other kinds of demand shocks to the energy market to be investigated, and sectoral price rigidities in the manner of Monacelli (2005). The framework makes use again the feature of convex costs in energy production as in Huynh (2012) 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 and also come to some agreements with results from previous works on the case of energy supply shock. We lean towards 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 did not differ in the opinion that the focus on inflation should be strong, but we only advocate it in the context of it being a support for a strong output stabilization stance, since focusing only on output tends to exacerbate the effects of the shocks. With Kormilitsina (2011), we are in the agreement that inflation should be accommodated, but as her conclusion left it quite inconclusive on the degree of output stimulation to pursue, our results went further in prescribing the policy that should accompany this inflation-accommodation stance.

We also shed light on the impact of alternative monetary regimes in the events of other kinds of energy price shocks, such as a TFP shock and demand shocks specific to the energy markets. A more aggregate shock to the energy market such as the TFP shock requires a wholly distinct policy reaction. In this case, it favors price stability. The two energy market specific demand shocks need policy intervention that is
qualitatively similar to the case of energy supply shock, but they do highlight im-
portant quantitative differences that cause the impact/effectiveness of various monetary
regimes to vary between them. In none of these shocks however does a desirable mon-
eyary response entail responding positively to energy price movements, if minimizing
the impact of high energy prices on output and consumption is the goal.

The explicit modeling of goods with different degree of energy dependency allowed
us to gain important insights into the inter-sectoral dynamics especially in terms of
prices and inflation. When the shock is more confined to the energy market, the surge
in the relative price of energy to the other goods can be very large, and the energy price
shock hits the energy-dependent goods and the non-energy-dependent goods quite dif-
ferently. The durables sector suffers comparatively more on its demand side than the
non-durables sector, which is affected primarily through its supply side. As a result
the inflation in the non-durables sector is always higher, and the size of this differential
is proportional to the degree to which the demand of durables is impacted. Our anal-
ysis on sectoral price rigidities indicate that the degree of price stickiness of the more
energy-dependent goods plays a greater role at amplifying or dampening the impact of
energy price shocks in the presence of monetary response, as the behavior of the less
energy-dependent goods sector is more sensitive to this price rigidity than vice versa.

Overall, we have revisited the energy supply shock debate and made our own
recommendations in terms of the more desirable monetary policy to follow. We also
extended the analysis to more energy price shocks and demonstrated how they might
need different policy prescriptions because of their distinct impact on the economy.
Even though our study did not employ welfare analysis, we believe that by focusing on
the behaviors of observables such as output and consumption the monetary authority
has a more feasible guidance on their policy conduct in response to energy price shocks.
References


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 1: 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.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>0.99</td>
<td>Time preference</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>0.34</td>
<td>Share of consumption in household’s utility</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.2</td>
<td>Share of durables in household’s consumption</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1 - 1/0.99</td>
<td>Durables-nondurables CES parameter</td>
</tr>
<tr>
<td>$\delta_k$</td>
<td>0.015</td>
<td>Capital depreciation rate</td>
</tr>
<tr>
<td>$a_1$</td>
<td>0.055</td>
<td>Param1 of durables depreciation function</td>
</tr>
<tr>
<td>$a_2$</td>
<td>0.3</td>
<td>Param2 of durables depreciation function</td>
</tr>
<tr>
<td>$\gamma_e$</td>
<td>0.6</td>
<td>Capital share of energy production function</td>
</tr>
<tr>
<td>$\gamma_d$</td>
<td>0.34</td>
<td>Capital share of durables production function</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>0.38</td>
<td>Capital share of nondurables production function</td>
</tr>
<tr>
<td>$\chi_d$</td>
<td>0.04659</td>
<td>Fixed cost of durables production</td>
</tr>
<tr>
<td>$\chi_n$</td>
<td>0.12735</td>
<td>Fixed cost of nondurables production</td>
</tr>
<tr>
<td>$\rho_A$</td>
<td>0.95</td>
<td>Persistence of non-energy sectors’ productivity process</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>0.95</td>
<td>Persistence of energy sector’s productivity process</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>0.95</td>
<td>AR1 coefficient of the exogenous process for $g$</td>
</tr>
<tr>
<td>$\omega_{k1}$</td>
<td>50</td>
<td>Param1 of capital adj. cost function</td>
</tr>
<tr>
<td>$\omega_{k2}$</td>
<td>1</td>
<td>Param2 of capital adj. cost function</td>
</tr>
<tr>
<td>$\omega_{d1}$</td>
<td>5</td>
<td>Param1 of durables adj. cost function</td>
</tr>
<tr>
<td>$\omega_{d2}$</td>
<td>1</td>
<td>Param2 of durables adj. cost function</td>
</tr>
<tr>
<td>$\omega_{B1}$</td>
<td>0.001</td>
<td>Param1 of portfolio adj. cost function</td>
</tr>
<tr>
<td>$\omega_{B2}$</td>
<td>1</td>
<td>Param2 of portfolio adj. cost function</td>
</tr>
<tr>
<td>$\omega_e$</td>
<td>3.77</td>
<td>Param1 of energy convex cost function</td>
</tr>
<tr>
<td>$\omega_d$</td>
<td>2</td>
<td>Param2 of energy convex cost function</td>
</tr>
<tr>
<td>$\pi^*$</td>
<td>1</td>
<td>Steady-state inflation</td>
</tr>
<tr>
<td>$R^*$</td>
<td>$1/\beta - 1$</td>
<td>Steady-state nominal interest rate</td>
</tr>
<tr>
<td>$\alpha_R$</td>
<td>0.8</td>
<td>Interest rate-smoothing weight</td>
</tr>
<tr>
<td>$\alpha_x$</td>
<td>0.2</td>
<td>Inflation weight</td>
</tr>
<tr>
<td>$\alpha_y$</td>
<td>0.09</td>
<td>Output weight</td>
</tr>
<tr>
<td>$\epsilon_d$</td>
<td>5</td>
<td>Elasticity of substitution among nondurables</td>
</tr>
<tr>
<td>$\epsilon_n$</td>
<td>5</td>
<td>Elasticity of substitution among durables</td>
</tr>
<tr>
<td>$\vartheta_d$</td>
<td>46</td>
<td>Scale factor of durables price adj. cost</td>
</tr>
<tr>
<td>$\vartheta_n$</td>
<td>46</td>
<td>Scale factor of nondurables price adj. cost</td>
</tr>
<tr>
<td>$\tau_d$</td>
<td>$(\epsilon_d - 1)/\vartheta_d$</td>
<td>Slope of durables Phillips Curve</td>
</tr>
<tr>
<td>$\tau_n$</td>
<td>$(\epsilon_n - 1)/\vartheta_n$</td>
<td>Slope of nondurables Phillips Curve</td>
</tr>
<tr>
<td>$\bar{m}\bar{c}_d$</td>
<td>$(\epsilon_d - 1)/\epsilon_d$</td>
<td>Steady-state durables real mc</td>
</tr>
<tr>
<td>$\bar{m}\bar{c}_n$</td>
<td>$(\epsilon_n - 1)/\epsilon_n$</td>
<td>Steady-state nondurables real mc</td>
</tr>
<tr>
<td>$\bar{\pi}_d$</td>
<td>1</td>
<td>Steady-state durables inflation</td>
</tr>
<tr>
<td>$\bar{\pi}_n$</td>
<td>1</td>
<td>Steady-state nondurables inflation</td>
</tr>
<tr>
<td>$\rho_{e,f}$</td>
<td>0.8</td>
<td>Persistence of firm energy tax</td>
</tr>
<tr>
<td>$\rho_{e,c}$</td>
<td>0.8</td>
<td>Persistence of household energy tax</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>0.8</td>
<td>Persistence of consumption tax</td>
</tr>
<tr>
<td>$\rho_i$</td>
<td>0.8</td>
<td>Persistence of income tax</td>
</tr>
<tr>
<td>$\phi_{e,f}$</td>
<td>0.12</td>
<td>Bond coefficient of firm energy tax</td>
</tr>
<tr>
<td>$\phi_{e,c}$</td>
<td>0.12</td>
<td>Bond coefficient of household energy tax</td>
</tr>
<tr>
<td>$\phi_e$</td>
<td>0.12</td>
<td>Bond coefficient of consumption tax</td>
</tr>
<tr>
<td>$\phi_i$</td>
<td>0.12</td>
<td>Bond coefficient of income tax</td>
</tr>
<tr>
<td>$\bar{\tau}_{e,f}$</td>
<td>0.1</td>
<td>Stead-state firm energy tax rate</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>$\bar{\tau}_c$</td>
<td>0.07</td>
<td>Stead-state consumption tax rate</td>
</tr>
<tr>
<td>$\bar{\tau}_{e,c}$</td>
<td>0.1</td>
<td>Stead-state household energy tax rate</td>
</tr>
<tr>
<td>$\bar{\tau}_i$</td>
<td>0.15</td>
<td>Stead-state income tax rate</td>
</tr>
<tr>
<td>$B$</td>
<td>1</td>
<td>Nominal bond target</td>
</tr>
<tr>
<td>$a$</td>
<td>0.06</td>
<td>Energy-intensity of durables</td>
</tr>
<tr>
<td>$b$</td>
<td>0.012</td>
<td>Energy-intensity of capital</td>
</tr>
</tbody>
</table>

Table 2: Calibrated Parameters
Section 4

Figure 1: Response of output to energy supply shock under interest rate peg (-*--) and baseline Taylor (-+-).

Figure 2: Response of output to a positive TFP shock to non-energy producers under interest rate peg (-*--) and baseline Taylor (-+-).
Figure 3: Response of output to a positive shock to household energy demand under interest rate peg (---) and baseline Taylor (-----)

Figure 4: Response of output to a positive shock to producers' energy demand under interest rate peg (---) and baseline Taylor (-----)
Section 5

Figure 5: response of output to monetary shock, with output weight at 0 and inflation weight going from 0 to 0.4

Figure 6: response of output to monetary shock, with output weight at 0.15 and inflation weight going from 0 to 0.4
Figure 7: response of output to monetary shock, with output weight at 0.3 and inflation weight going from 0 to 0.4

Figure 8: response of energy price to monetary shock, with output weight at 0 and inflation weight going from 0 to 0.4
Figure 9: response of energy price to monetary shock, with output weight at 0.15 and inflation weight going from 0 to 0.4

Figure 10: response of energy price to monetary shock, with output weight at 0.3 and inflation weight going from 0 to 0.4
Section 6.1

Figure 11: response of output to energy supply shock, with output weight at 0 and inflation weight going from 0 to 0.4

Figure 12: response of output to energy supply shock, with output weight at 0.15 and inflation weight going from 0 to 0.4
Figure 13: response of output to energy supply shock, with output weight at 0.3 and inflation weight going from 0 to 0.4

Figure 14: response of inflation to energy supply shock, with output weight at 0 and inflation weight going from 0 to 0.4
Figure 15: response of inflation to energy supply shock, with output weight at 0.15 and inflation weight going from 0 to 0.4

Figure 16: response of inflation to energy supply shock, with output weight at 0.3 and inflation weight going from 0 to 0.4
Figure 17: response of interest rate to energy supply shock, with output weight at 0 and inflation weight going from 0 to 0.4

Figure 18: response of interest rate to energy supply shock, with output weight at 0.15 and inflation weight going from 0 to 0.4
Figure 19: response of interest rate to energy supply shock, with output weight at 0.3 and inflation weight going from 0 to 0.4

Figure 20: variance of output at output weights = 0 (-*-), 0.15 (-+-) and 0.3 (-), with inflation weight going from 0 to 0.4
Figure 21: variance of inflation at output weights = 0 (---), 0.15 (--+) and 0.3 (--), with inflation weight going from 0 to 0.4.

Figure 22: variance of consumption at output weights = 0 (---), 0.15 (--+) and 0.3 (--), with inflation weight going from 0 to 0.4.
Section 6.2

Figure 23: response of output to a positive TFP shock to non-energy producers, with output weight at 0 and inflation weight going from 0 to 0.4

Figure 24: response of output to a positive TFP shock to non-energy producers, with output weight at 0.15 and inflation weight going from 0 to 0.4
Figure 25: response of output to a positive TFP shock to non-energy producers, with output weight at 0.3 and inflation weight going from 0 to 0.4

Figure 26: response of inflation to a positive TFP shock to non-energy producers, with output weight at 0 and inflation weight going from 0 to 0.4
Figure 27: response of inflation to a positive TFP shock to non-energy producers, with output weight at 0.15 and inflation weight going from 0 to 0.4

Figure 28: response of inflation to a positive TFP shock to non-energy producers, with output weight at 0.3 and inflation weight going from 0 to 0.4
Figure 29: response of interest rate to a positive TFP shock to non-energy producers, with output weight at 0 and inflation weight going from 0 to 0.4

Figure 30: response of interest rate to a positive TFP shock to non-energy producers, with output weight at 0.15 and inflation weight going from 0 to 0.4
Figure 31: response of interest rate to a positive TFP shock to non-energy producers, with output weight at 0.3 and inflation weight going from 0 to 0.4

Figure 32: response of capital stock to a positive TFP shock to non-energy producers under strong inflation-only focus (-*) and under strong output-only focus (+-+)

Section 6.3

Figure 33: response of output to a positive shock to household energy demand, with output weight at 0 and inflation weight going from 0 to 0.4

Figure 34: response of output to a positive shock to household energy demand, with output weight at 0.15 and inflation weight going from 0 to 0.4
Figure 35: response of output to a positive shock to household energy demand, with output weight at 0.3 and inflation weight going from 0 to 0.4

Figure 36: response of output to a positive shock to producers’ energy demand, with output weight at 0 and inflation weight going from 0 to 0.4
Figure 37: response of output to a positive shock to producers’ energy demand, with output weight at 0.15 and inflation weight going from 0 to 0.4

Figure 38: response of output to a positive shock to producers’ energy demand, with output weight at 0.3 and inflation weight going from 0 to 0.4
Figure 39: response of inflation to a positive shock to household energy demand under strong inflation-only focus (-+-) and under the interest rate peg (-*-).

Figure 40: response of inflation to a positive shock to producers’ energy demand under strong inflation-only focus (-+-) and under the interest rate peg (-*-).
Figure 41: response of capital investment to a positive shock to household energy demand under strong inflation-only focus (-+-) and under the interest rate peg (-*-).

Figure 42: response of capital investment to a positive shock to producers’ energy demand under strong inflation-only focus (-+-) and under the interest rate peg (-*-).
Figure 43: response of output to a positive shock to household energy demand under strong dual mandate (---) and under the interest rate peg (---)

Figure 44: response of output to a positive shock to producers’ energy demand under strong dual mandate (---) and under the interest rate peg (---)
Section 7.1

Figure 45: responses of durables price (\(-^*\)) and nondurables prices (\(-^+\)) to energy supply shock under interest rate peg

Figure 46: responses of durables price (\(-^*\)) and nondurables prices (\(-^+\)) to a positive shock to household energy demand under interest rate peg
Figure 47: responses of durables price (-*--) and nondurables prices (-+-) to a positive shock to producers’ energy demand under interest rate peg.

Figure 48: responses of durables price (-*--) and nondurables prices (-+-) to a positive TFP shock to non-energy producers under interest rate peg.
Section 7.2

Figure 49: Response of output to energy supply shock at three degrees of non-durables price rigidity under baseline Taylor rule.

Figure 50: Response of output to energy supply shock at three degrees of durables price rigidity under baseline Taylor rule.
Figure 51: 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 52: 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 Equilibrium Conditions

Household’s first order conditions

Euler equation for durables

\[
(1 - \alpha)^{1-\rho} \frac{p_{d,t}}{p_{n,t}} c_t^{-\rho} n_t^{\rho - 1} \left( 1 + \frac{\omega_{d1}}{d_t} \left( \frac{d_{t+1} - d_t}{d_t} \right)^{\omega_{d2}} \right) = \beta E(1-\rho) c_{t+1}^{-\rho} (u_{t+1} d_{t+1})^{\rho - 1} u_{t+1} + E(1-\rho) c_{t+1}^{-\rho} [\omega_{d2} + \omega_{d1}^2 \left( \frac{d_{t+1} - d_t}{d_{t+1}} \right)^{\omega_{d2}}]
\]

Euler equation for capital

\[
\frac{p_{d,t}}{(1 + \pi_{t}) p_{n,t}} c_t^{-\rho} n_t^{\rho - 1} \left( 1 + \frac{\omega_{k1}}{k_t} \left( \frac{k_{t+1} - k_t}{k_t} \right)^{\omega_{k2}} \right) = \beta E(1-\rho) c_{t+1}^{-\rho} n_{t+1}^{\rho - 1} \left( 1 + \pi_{t+1} \right) n_{t+1} \left( 1 - \delta_{t+1} + \frac{\omega_{k1} k_{t+1}}{k_{t+1}^2} \left( \frac{k_{t+2} - k_{t+1}}{k_{t+1}} \right)^{\omega_{k2}} \right)
\]

Euler equation for bond

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

Intra-temporal nondurables-labor

\[
(1 - \alpha)^{1-\rho} \frac{\varphi}{1 - \varphi} (1 - h_t) c_t^{-\rho} n_t^{\rho - 1} = \frac{1 + \pi_{t} p_{n,t}}{1 - \pi_{t} t} w_t
\]

Intra-temporal nondurables-utilization

\[
\frac{(1 - \alpha)^{1-\rho} n_t^{\rho - 1}}{\alpha^{1-\rho} (u_t d_t)^{\rho - 1}} = \frac{(1 + \pi_{t}) p_{n,t}}{a(1 + \pi_{t}) p_{c,t} + (1 + \pi_{t}) p_{d,t} \delta_{d,t}}
\]

with

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

Budget constraint

\[
(1 + \pi_{t}) p_{c,t} \omega h_t + (1 + \pi_{t}) p_{n,t} n_t + (1 + \pi_{t}) p_{d,t} i_{d,t} + p_{d,t} i_{k,t} + i_{B,t} = (1 - \pi_{t}) (w_t h_t + r_t k_t) + R_t B_t
\]

Investment adjustment costs and variable depreciation

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

\[
i_{k,t} = k_{t+1} - (1 - \delta_{k}) k_t + \frac{\omega_{k1}}{1 + \omega_{k2}} \left( \frac{k_{t+1} - k_t}{k_t} \right)^{1+\omega_{k2}}
\]
\[ i_{B,t} = B_{t+1} - B_t + \frac{\omega B_1}{1 + \omega B_2} (B_{t+1} - \bar{B})^{1+\omega B_2} \]
\[ \delta_{d,t} = \frac{a_1}{a_2 + 1} u_t^{a_2+1} \]

**Sectors’ aggregate outputs**
\[ y_{e,t} = \exp(A_{e,t})k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e} \]
\[ b_{e,t} = \frac{\omega e_1}{(1 + \omega e_2)} (k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e})^{1+\omega e_2} \]
\[ y_{i,t} = \exp(A_t) (k_{i,t})^{\gamma_i} (h_{i,t})^{1-\gamma_i} - \chi_i \]
with \( i = d, n \)

**Firms’ first order conditions**
\[ mc_{i,t}\exp(A_t)(1 - \gamma_i) \left( \frac{k_{i,t}}{h_{i,t}} \right)^{\gamma_i} = \frac{w_t}{p_{i,t}} \]
\[ \frac{1 - \gamma_i k_{i,t}}{\gamma_i h_{i,t}} = \frac{w_t}{r_t + bp_{e,t}(1 + \tau_{e,f,t})} \]
\[ p_{e,t}\exp(A_{e,t})^{\gamma_e} \left( \frac{k_{e,t}}{h_{e,t}} \right)^{\gamma_e-1} = r_t + b_{e,t}p_{e,t}(1 + \tau_{e,f,t}) + k_{e,t}p_{e,t}(1 + \tau_{e,f,t})b_{e,t}h_{e,t}\exp(1 - \gamma_e)k_{e,t}^{-\gamma_e} \]
\[ p_{e,t}\exp(A_{e,t})(1 - \gamma_e) \left( \frac{k_{e,t}}{h_{e,t}} \right)^{\gamma_e} = w_t + k_{e,t}p_{e,t}(1 + \tau_{e,f,t})b_{e,t}h_{e,t}\exp(1 - \gamma_e)k_{e,t}^{-\gamma_e} \]

**Sectoral Phillips curves**
\[ \hat{\pi}_{i,t} = \beta E_{\hat{\pi}_{i,t+1}} + \frac{\epsilon_i - 1}{\phi_i} \hat{\pi}_{c,t} \]
with \( i = d, n \)

**Fiscal and monetary policies**

**Government budget constraint**
\[ \tau_{e,c,t}p_{e,t}a_{i,t}d_t + \tau_{e,f,t}p_{e,t}(b(k_{d,t} + k_{n,t}) + b_{e,t}k_{e,t}) + \tau_{c,t}(p_{n,t}n_t + p_{d,t}d_{i,t}) + \tau_{i,t}(r_tk_t + w_t h_t) + i_{B,t} = p_t g_t y_t + R_t B_t \]

**Tax rules**
\[ \log \left( \frac{\tau_{(t),t}}{\tau_{(0),t}} \right) = \rho_{(t)} \log \left( \frac{\tau_{(t-1),t-1}}{\tau_{(0),t}} \right) + \phi_{(t)} \log \left( \frac{B_t}{B} \right) \]
with \((t) = (e, c), (e, f), c, i \)

**Monetary policy function**
\[ R_t - R^* = \alpha_R (R_{t-1} - R^*) + \alpha_y (\pi_t - \pi^*) + \alpha_y (y_t - y_{t-1}) + \epsilon_{c,t} \]
Market clearing

\[ k_t = k_{d,t} + k_{n,t} + k_{e,t} \]
\[ h_t = h_{d,t} + h_{n,t} + h_{e,t} \]
\[ y_{d,t} = i_{d,t} + i_{k,t} + g_{d,t} + \frac{\bar{d}}{2}(\pi_{d,t} - 1)^2 y_{d,t} \]
\[ y_{n,t} = n_t + g_{n,t} + \frac{\bar{n}}{2}(\pi_{n,t} - 1)^2 y_{n,t} \]
\[ g_t y_t = \left[ \alpha^{1-\rho} g_{d,t}^{\rho} + (1 - \alpha)^{1-\rho} g_{n,t}^{\rho} \right]^{1/\rho} \]
\[ p_t g_t y_t = p_{d,t} g_{d,t} + p_{n,t} g_{n,t} + p_{e,t} a g_{d,t} \]

Aggregate price and aggregate value add

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

Exogenous shock process

\[ A_t = \rho A_{t-1} + \epsilon_A,t \]
\[ A_{e,t} = \rho e A_{e,t-1} + \epsilon_{e,t} \]
\[ g_t = \rho g g_{t-1} + \epsilon_{g,t} \]