

# **Energy Price Uncertainty and Decreasing Pass-through to Core Inflation**

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# Energy Price Uncertainty and Decreasing Pass-through to Core Inflation\*

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## Abstract

This paper uses an extended version of the New Keynesian model to provide an alternate explanation for the decrease in energy price pass-through to core inflation. Results show that in a model with households' consumption of energy goods, uncertain energy prices decrease firms' responsiveness to an energy price shock. This is due to the upward pricing bias channel in firms' pricing decision. Since prices are sticky, firms bias their prices upwards. The pricing bias provides cushion to firms against future cost shocks. Increase in energy price uncertainty further increases the magnitude of the bias. As a result, when a positive energy price shock hits the economy, firms require a smaller increase in their prices than they would have in absence of the pricing bias.

**Keywords:** Energy Prices; Uncertainty; Inflation; Monetary Policy; DSGE.

**JEL Classification Numbers:** E31, E52, E58.

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# 1 Introduction

The consequence of energy price changes for the macroeconomy, especially for inflation, form an important question for central banks. Hooker (2002) and Blanchard and Gali (2010) show that the pass-through from energy prices to inflation has decreased for the period since the 1980s. Hooker investigates whether the observed decrease in energy price pass-through is due to aggressive monetary policy responses to inflation since the time of Paul Volcker. However, he finds that monetary policy has instead become less responsive to energy price shocks over the same period and, therefore, cannot be an adequate explanation for the decrease in pass-through. Blanchard and Gali go further to explore the structural reasons which may help explain the observed decline in energy price pass-through. They find the decrease in energy share in both households' consumption and firms' production to be one of the contributing factors. They also find the decrease in wage rigidities and increase in monetary policy credibility as important towards explaining changes in the effect of energy price shocks.

This paper focuses on core inflation dynamics instead of aggregate inflation dynamics in response to an energy price shock. As in Blanchard and Gali, I provide a structural explanation for the decrease in pass-through from energy prices to core inflation. I particularly focus on the effect of energy price uncertainty and the share of energy in households' consumption relative to the share in firms' production (i.e. relative share). However, before discussing the model framework and the key results, let me briefly explain the motivation for focusing on these two factors. I first discuss the motivation for the relative share. In data provided in Blanchard and Gali, the

share of oil in firms' production has declined more than the share in households' consumption. As a result, the relative share of oil in households' consumption has increased. A similar trend can be seen for energy goods as a whole.<sup>1</sup> The motivation for considering the implication of energy price uncertainty for core inflation comes from Edelstein and Kilian (2009) and Elder and Serletis (2010). Edelstein and Kilian (2009) and Elder and Serletis (2010) show that energy price uncertainty has indeed increased since the 1990s. They find energy prices to be most volatile during the 2000s.<sup>2</sup> An increase in energy price uncertainty and the relative share of energy in consumption motivates the question whether firms have also changed in how they respond to energy price shocks. I will show that both these changes have important implications for energy price pass-through to core inflation.

I use an extended version of the New Keynesian DSGE model to study the effect of energy price uncertainty and an increase in the relative share of energy in consumption on core inflation. Specifically, as in Kara and Pirzada (2016), I allow for the domestic production of energy goods which are then used for finished goods production and households' consumption.<sup>3</sup> Since energy goods are consumed by both finished-goods producing firms and households, a positive energy price shock

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<sup>1</sup>According to the Use-tables provided by the Bureau of Economic Analysis, the share of energy in production decreased from 6.9% in 1977 to 2.9% in 1997. The share of energy in household consumption expenditure decreased relatively less from 6.5% in 1977 to 4% in 1997% (U.S. Energy Information Administration). The relative share of energy in households' consumption has increased from 0.9 (i.e. 6.4/6.9) in 1977 to 1.4 (i.e. 4/2.9) in 1997.

<sup>2</sup>Edelstein and Kilian (2009) specifically focus on the effect of energy price changes on households' purchasing power. They note that the increase in the volatility of households' purchasing power - driven by changes in energy prices - is also robust to changes in the share of energy in households' consumption. This implies that increase in the volatility of households' purchasing power is not driven by changes in the share of energy in households' consumption but is due to an increase in energy price volatility.

<sup>3</sup>These goods could include gasoline, diesel, electricity produced using domestic fuel sources etc.

affects core inflation through two important channels - the production channel and the consumption channel. Firstly, an increase in the energy price increases firms' marginal costs which puts upward pressure on core inflation. This is the production channel. Secondly, an increase in the energy price also decreases households' demand for finished consumption goods thus putting downward pressure on core inflation. This is the consumption channel. Finally, in order to fully capture the effect of energy price uncertainty on macroeconomic variables, I take a third-order Taylor-approximation of the model solution. This is in line with the literature studying the role of uncertainty in driving business cycle dynamics (Basu and Bundick (2015), Bloom (2009), Born and Pfeifer (2014), Fernandez-Villaverde et al. (2008), Plante and Traum (2014) and Gilchrist et al. (2014) amongst others).

In the new model, core inflation dynamics in response to an energy price shock depend on the relative importance of the production and the consumption channels. When the relative share of energy in households' consumption is zero (so the consumption channel is absent), finished-goods producing firms always increase their prices in response to an increase in their marginal costs. As a result, core inflation increases. However, as the relative share increases (so the consumption channel becomes more important), an increase in the energy price also puts downward pressure on core inflation. This is because an increase in the energy price reduces households' purchasing power which subsequently reduces households' demand for finished consumption goods. Consequently, core inflation increases less. I refer to this as the deflationary effect of an energy price shock.

Additionally, and more importantly, when households consume energy goods, un-

certain energy prices further amplify the deflationary effect of energy price shocks. I explore two possible reasons for why an increase in energy price uncertainty amplifies the deflationary effect: precautionary savings motive of the households; and, upward pricing bias channel in firms' pricing decision. I first discuss the role of precautionary savings. I find that the precautionary savings motive cannot explain the amplification effect of higher energy price uncertainty, following an energy price shock. This is because higher precautionary savings motive causes households to save more. These precautionary savings can be seen as a form of self-insurance which provides a cushion against adverse future shocks. As a result, when the economy is hit by a positive energy price shock, consumption falls less than it would have in absence of precautionary savings. Highlighting the role precautionary savings in decreasing the pass-through from energy prices to the real economy is another important contribution of this paper.

I now turn to the upward pricing bias channel. Fernandez-Villaverde et al. (2015) explain the role of upward pricing bias channel in the context of fiscal volatility shocks. As shown in Fernandez-Villaverde et al. (2015), the profit function of firms is asymmetric such that losses are higher when firm's price relative to its competitors is lower than when it is higher. Since prices cannot be adjusted every period, firms bias their prices upwards. When uncertainty about future price level is higher, magnitude of the pricing bias increases. As in the case of precautionary savings, upward pricing bias can also be imagined as a form of self-insurance against future cost shocks. Therefore, when a positive cost shock hits the economy, optimising firms require a smaller increase in their prices than they would have in absence of the upward pricing

bias.

The upward pricing bias channel can explain the amplification effect of higher energy price uncertainty in this paper. Since energy goods are also consumed by households, higher energy price uncertainty also makes the aggregate price level more uncertain. Consequently, for reasons discussed above, firms allow for large pricing bias. When a positive energy price shock hits the economy, price setting firms require a smaller increase in their prices due to the existence of pricing bias. When the bias is significantly large, the required increase in prices is significantly smaller such that core inflation falls below its steady state.

This paper is closely related to Plante and Traum (2014) and Blanchard and Gali (2010). Plante and Traum study the effect of an oil price uncertainty shock on core inflation. They find that firms increase their prices in response to an increase in oil price uncertainty. This is due to the upward pricing bias channel explained in Fernandez-Villaverde et al. (2015). However, different from this paper, Plante and Traum do not study the implication of oil price uncertainty for the effect of oil price shocks. Moreover, they also abstract from the discussion of changes in the relative share of energy in households' consumption. The share of oil in consumption and production is fixed at 2%. On the other hand, Blanchard and Gali highlight the importance of the decrease in both the consumption and the production share of energy in explaining part of the decrease in energy price pass-through. However, they focus on aggregate inflation rather than core inflation.

Other studies have focused on the effect of energy prices on overall economic activity. Hamilton (1983) showed that increases in energy prices have been associated

with significant contractions in US economic activity since the Second World War. While Hooker (1996) notes that the pass-through from the energy price to economic activity has decreased significantly, Hamilton (1996, 2003, 2011) finds that the underlying relationship between energy price increases and economic activity remains stable. This is because, according to Hamilton, the true relationship between energy prices and economic activity is nonlinear and asymmetric. It is this nonlinear and asymmetric relationship which Hamilton suggests is stable.<sup>4</sup> However, Kilian and Vigfusson (2011a, 2011b) find little evidence for the asymmetric relationship emphasised by Hamilton.<sup>5</sup>

The rest of the paper is organised as follows. Section 2 describes the model. Section 3 discusses the calibration of the model. The main results and the role of energy price uncertainty in determining core inflation dynamics are explained in section 4. In section 5, I discuss the role of nominal rigidities in driving the results in section 4. Finally, section 6 concludes.

## 2 Model

The framework in this paper is a special case of the analysis in Kara and Pirzada (2016).<sup>6</sup> That model is useful since it allows for endogenous production of intermediate materials and therefore endogenous intermediate materials prices. This paper

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<sup>4</sup>While increases in energy prices have significant effects, decreases in energy prices do not. Hamilton further argues that increases in energy prices which are a revision to an earlier decrease have only limited effects.

<sup>5</sup>For Hamilton's response to Kilian and Vigfusson, see Hamilton (2011).

<sup>6</sup>Kara and Pirzada (2016) also incorporates the Bernanke et al. (1999) financial accelerator mechanism which is not included here.



calibrates the Kara and Pirzada model for energy goods production.

The model in Kara and Pirzada (2016) allows for firm level heterogeneity such that there is a continuum of intermediate firms within each of the two sectors - energy and finished goods - producing differentiated goods. The final goods producers in both sectors aggregate the sector-specific differentiated goods to produce a sector-specific final good. The final goods produced in the energy sector are then used by the finished-goods producing firms to produce finished consumption goods and are also directly consumed by the households.

The domestic production of energy goods allows energy prices to be determined endogenously. Energy prices in the new model depend on energy goods producing firms' marginal costs and an exogenous energy price shock. Barsky and Kilian (2004) and Kilian (2008) have noted that energy prices are not exogenous to changes in the US economy. The structure of the model is, therefore, an attempt to capture the endogeneity of energy prices to changes in the macroeconomy. In contrast, similar models in the literature assume that energy goods are imported and energy prices are exogenously determined.

The rest of the model is standard New Keynesian. There is a continuum of households who consume, save and provide labor. There are labor packers who aggregate the differentiated household labor into a homogeneous input and sell it to the firms in both energy and finished-goods producing sectors at the same price. Finally, the central bank conducts monetary policy according to a Taylor-type rule.

Section 2.1 explains the interaction between energy and the finished goods sector firms.

## 2.1 Energy and Finished Goods Sectors

The model assumes a continuum of firms,  $f \in [0, 1]$ , in both energy and finished goods producing sectors. Goods produced in the energy sector ( $e$ ) are used as an additional factor input by firms in the finished goods sector ( $s$ ) and also consumed by the households. Finished goods producing firms use energy materials produced in sector ‘ $e$ ’ to produce finished consumption goods. The remaining fraction of energy goods - not used in finished goods production - is directly consumed by households. Aggregation is done according to a Dixit-Stiglitz aggregator such that aggregate consumption is:

$$C_t = [\Psi^{(1/\tau)}(C_t^e)^{\frac{\tau-1}{\tau}} + (1 - \Psi)^{(1/\tau)}(C_t^s)^{\frac{\tau-1}{\tau}}]^{\frac{\tau}{\tau-1}} \quad (1)$$

where  $\Psi$  is the weight on energy goods in the consumption basket.  $\tau$  is the elasticity of substitution between energy and finished goods.  $C_t^e$  and  $C_t^s$  are the energy goods and finished goods consumed by the households, respectively. The corresponding price index is:

$$P_t = [\Psi(P_t^e)^{(1-\tau)} + (1 - \Psi)(P_t^s)^{(1-\tau)}]^{\frac{1}{1-\tau}} \quad (2)$$

where  $P_t^e$  is the price index in the energy sector and  $P_t^s$  is the price index in the finished goods sector.  $P_t$  is the consumer price index. Final good producers in each sector aggregate the sector-specific intermediate goods to produce sector-specific final goods according to production functions of the form:

$$Y_t^e = \left[ \int_0^1 (Y_{f,t}^e)^{\frac{\rho-1}{\rho}} df \right]^{\frac{\rho}{1+\rho}} \quad (3)$$

$$Y_t^s = \left[ \int_0^1 (Y_{f,t}^s)^{\frac{\epsilon-1}{\epsilon}} df \right]^{\frac{\epsilon}{1+\epsilon}} \quad (4)$$

where  $Y_{f,t}^e$  and  $Y_{f,t}^s$  represent the differentiated goods produced by individual firms in each sector. The demand functions associated with individual firms in the two sectors are:

$$Y_{f,t}^e = \left( \frac{P_{f,t}^e}{P_t^e} \right)^{-\rho} Y_t^e; \quad \text{where, } Y_t^e = \left( \frac{P_t^e}{P_t} \right)^{-\tau} \Psi Y_t \quad (5)$$

$$Y_{f,t}^s = \left( \frac{P_{f,t}^s}{P_t^s} \right)^{-\epsilon} Y_t^s; \quad \text{where, } Y_t^s = \left( \frac{P_t^s}{P_t} \right)^{-\tau} (1 - \Psi) Y_t \quad (6)$$

where  $P_{f,t}^e$  and  $P_{f,t}^s$  represent firm-specific prices in sectors  $e$  and  $s$ , respectively.

### 2.1.1 Intermediate Energy Sector Firms

Firms in the energy sector use only two factor inputs - capital and labor - to produce energy goods. Production is done according to a Cobb-Douglas production function of the form:

$$Y_{f,t}^e = A_t (K_{f,t}^e)^\alpha (L_{f,t}^e)^{1-\alpha} - z_t \Phi \quad (7)$$

where  $K_{f,t}^e$  and  $L_{f,t}^e$  are firm-specific capital services and labor inputs, respectively.  $\alpha$  is the output-capital elasticity in firms' production.  $A_t$  is total factor productivity (TFP) and follows the following AR(1) process:

$$A_t = A_{t-1} \exp(\Lambda_a + z_{a,t}) \quad (8)$$

where  $z_{a,t} = \sigma_a \epsilon_{a,t}$  and  $\epsilon_{a,t} \sim N(0, 1)$ .  $\sigma_a$  is the standard deviation of the i.i.d. shock,  $\epsilon_a$ .  $\Lambda_a$  determines the steady-state TFP growth rate. The shock process for TFP generates the first unit root in the model and is one of two sources of growth in the economy.

The parameter  $\Phi$  in equation (7) is the fixed cost which grows at the rate of economic growth,  $z_t$ .  $z_t$  is a combination of TFP and investment-specific technology

growth and is given by:

$$z_t = A_t^{\frac{1}{1-\alpha}} \mu_t^{\frac{\alpha}{1-\alpha}} \quad (9)$$

where the steady-state growth rate of the economy is  $\left(\frac{\Lambda_a + \alpha \Lambda_\mu}{1-\alpha}\right)$  and the corresponding shock equals  $\left(\frac{z_{a,t} + \alpha z_{\mu,t}}{1-\alpha}\right)$ .  $\mu_t$  is the investment-specific technology shock.  $\mu_t$  generates the second unit root in the model and is important towards accounting for the decline in the relative price of capital observed since the Second World War for the US.  $\mu_t$  follows a similar process as in equation (8):

$$\mu_t = \mu_{t-1} \exp(\Lambda_\mu + z_{\mu,t}) \quad (10)$$

where  $z_{\mu,t} = \sigma_\mu \epsilon_{\mu,t}$  and  $\epsilon_{\mu,t} \sim N(0, 1)$ .  $\sigma_\mu$  is the parameter for the shock process in equation (10).  $\Lambda_\mu$  determines the steady-state investment-specific technology growth rate.

Energy sector firms minimise their real cost in equation (11) subject to their production function. Each firm is assumed to be a price taker for both factor inputs.

$$\min_{L_{f,t}^e, K_{f,t}^e} w_t L_{f,t}^e + r_t^k K_{f,t}^e \quad (11)$$

where  $w_t$  and  $r_t$  are real wages and real rental rate of capital. Since all firms face the same input prices, the real marginal cost for each firm in the energy sector is also identical and is given by:

$$mc_t^e = \frac{w_t^{1-\alpha} (r_t^k)^\alpha}{\alpha^\alpha (1-\alpha)^{1-\alpha} A_t} \quad (12)$$

Firms set their prices according to the Calvo pricing mechanism. In line with micro-evidence on price setting in the energy sector, it is assumed that energy prices are fully flexible (Klenow and Malin (2011)). Therefore, the optimal real price in the

energy sector is:

$$p_{f,t}^{e*} = \frac{\rho}{\rho - 1} \nu_t m c_t^e \quad (13)$$

where  $p_{f,t}^{e*}$  is the optimal real price of energy goods and is equal to  $p_t^{e*}$  under the assumption of symmetric equilibrium. In addition to the endogenous changes in  $p_t^{e*}$  through changes in  $m c_t^e$ , the real energy price is also driven by exogenous energy price shocks,  $\nu_t$ .  $\nu_t$  follows an AR(1) process of the form:

$$\nu_t = \nu_{t-1}^{\rho_\nu} \exp(z_{\nu,t}) \quad (14)$$

where  $z_{\nu,t} = \sigma_\nu \epsilon_{\nu,t}$  and  $\epsilon_{\nu,t} \sim N(0, 1)$ .  $\sigma_\nu$  and  $\rho_\nu$  are the two parameters for the shock process in equation (14). Nominal inflation in the energy sector,  $\pi_t^e$ , is:

$$\pi_t^e = \frac{p_t^{e*}}{p_{t-1}^{e*}} \pi_t \quad (15)$$

where  $\pi_t$  is aggregate inflation in the economy.

### 2.1.2 Intermediate Finished Goods Sector Firms

Firms in the finished goods sector use energy goods as an additional factor input in their production:

$$Y_{f,t}^s = A_t [(K_{f,t}^s)^\alpha (L_{f,t}^s)^{(1-\alpha)}]^{(1-\mu)} (E_t^f)^\mu - z_t \Phi \quad (16)$$

where  $K_{f,t}^s$  and  $L_{f,t}^s$  are capital services and labor inputs in finished goods production.  $\mu$  is the output elasticity with respect to energy inputs,  $E_t^f$ , in production. Firms minimise their real cost in equation (17) subject to their production function:

$$\min_{L_{f,t}^s, K_{f,t}^s, Y_t^e} w_t L_{f,t}^e + r_t^k K_{f,t}^e + p_t^{e*} E_t^f \quad (17)$$

where the prices of labor, capital and energy goods are given by  $w_t$ ,  $r_t^k$  and  $p_t^{e*}$ , respectively. Firms in both the energy and the finished goods sector are assumed to face similar real input prices for labor and capital. The real marginal cost for finished goods firms is therefore:

$$mc_t^s = \frac{w_t^{(1-\alpha)(1-\mu)} (r_t^k)^{\alpha(1-\mu)} (p_t^e)^\mu}{\alpha^{\alpha(1-\mu)} [(1-\alpha)(1-\mu)]^{(1-\alpha)(1-\mu)} (\mu)^\mu A_t} \quad (18)$$

Prices in the finished goods sector are sticky and are set according to Calvo (1983). Firms reoptimise their prices every period with a probability of  $(1 - \zeta_p)$ . The first-order conditions of the firms' profit maximisation problem are:

$$\begin{aligned} g_t^2 &= \lambda_t mc_t^s Y_t^s + \beta \zeta_p \mathbb{E} \left( \frac{(\pi_t^s)^{\iota_p}}{\pi_{t+1}^s} \right)^{-\epsilon} g_{t+1}^1 \\ g_t^1 &= \lambda_t \Pi_t^* Y_t^s + \beta \zeta_p \mathbb{E} \left( \frac{(\pi_t^s)^{\iota_p}}{\pi_{t+1}^s} \right)^{1-\epsilon} \left( \frac{\Pi_t^*}{\Pi_{t+1}^*} \right) g_{t+1}^2 \end{aligned} \quad (19)$$

where  $\epsilon g_t^1 = (\epsilon - 1) g_t^2$ .  $\pi_t^s$  is the finished goods sector inflation and

$$\Pi_t^* = \frac{P_t^{s*}}{P_t^s} \quad (20)$$

From hereon,  $\pi_t^s$  is also referred to as core inflation. The price index in the finished goods sector,  $P_t^s$ , evolves such that:

$$1 = \zeta_p \left( \frac{(\pi_{t-1}^s)^{\iota_p}}{\pi_t^s} \right)^{1-\epsilon} + (1 - \zeta_p) \Pi_t^{*(1-\epsilon)} \quad (21)$$

## 2.2 Households

There is a continuum of households indexed  $j \in [0, 1]$ . Households maximise their lifetime utility in equation (22) and provide labor to both energy and finished goods

sectors:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t b_t \left[ \log(C_{j,t} - hC_{j,t-1}) - \varphi_t \psi \frac{L_{j,t}^{1+\sigma_l}}{1+\sigma_l} \right] \quad (22)$$

subject to their budget constraint:

$$C_{j,t} + I_{j,t} + \frac{B_{j,t+1}}{P_t} \leq \frac{R_{j,t-1} B_{j,t}}{P_t} + W_{j,t} L_{j,t} + (R_t^k u_{j,t} - a(u_{j,t})) \bar{K}_{j,t-1} + T_t + \Gamma_t \quad (23)$$

and

$$\bar{K}_{j,t} = (1 - \delta) \bar{K}_{j,t-1} + \mu_t \left( 1 - S \left[ \frac{I_{j,t}}{I_{j,t-1}} \right] \right) I_{j,t} \quad (24)$$

where  $C_{j,t}$ ,  $I_{j,t}$  and  $B_{j,t+1}$  represent households' consumption, investment and bond purchases.  $L_{j,t}$  is labor hours and  $\bar{K}_{j,t}$  is capital stock. Households also make capital utilisation decisions,  $u_{j,t}$ , every period and rent capital services,  $K_{j,t}$ , to the firms (i.e.  $K_{j,t} = u_{j,t} \bar{K}_{j,t-1}$ ).  $W_{j,t}$ ,  $R_t^k$  and  $R_t$  are the nominal wage, nominal return on capital services and nominal return on bonds, respectively.  $\beta$  is the discount factor,  $h$  is habit persistence in consumption and  $\sigma_l$  is the inverse of the Frisch labor supply elasticity.

$b_t$  and  $\mu_t$  are two exogenous shocks to household intertemporal preferences and labor supply, respectively.  $b_t$  follows an AR(1) process of the form in equation (14).  $T_t$  are lump-sum tax transfers to the households and  $\Gamma_t$  represent firms' profits in the economy. Firms are owned by the households.  $a(u_{j,t})$  is the cost of capital utilisation, respectively. It is standard in the literature to assume  $a(1) = 0$ ,  $a'$  and  $a'' > 0$ .

Capital evolves according to equation (24).  $\delta$  is the rate of depreciation and  $S[\cdot]$  is an adjustment cost function of the form:

$$S \left[ \frac{I_t}{I_{t-1}} \right] = \frac{\kappa}{2} \left( \frac{I_t}{I_{t-1}} - \Lambda_\mu \right)^2 \quad (25)$$

such that  $S[\Lambda_\mu] = 0$ ,  $S'[\Lambda_\mu] = 0$  and  $S''[\Lambda_\mu] > 0$ .  $\kappa \geq 0$  and  $\Lambda_\mu$  is the steady state

investment-specific technology growth rate.

Labor packers buy the sector-specific labor from the households and provide it to firms in both sectors according to the production functions:

$$L_t^e = \left( \int_0^1 (L_{j,t}^e)^{\frac{\eta-1}{\eta}} dj \right)^{\frac{\eta}{\eta-1}} \quad (26)$$

and

$$L_t^s = \left( \int_0^1 (L_{j,t}^s)^{\frac{\eta-1}{\eta}} dj \right)^{\frac{\eta}{\eta-1}} \quad (27)$$

where  $\eta$  is the elasticity of substitution among different types of labor within each sector. Labor packers maximise their profits subject to their production function. For simplicity, I assume that wages in both sectors are similar such that the first-order conditions give a standard wage Phillips Curve:

$$\begin{aligned} f_t &= \left( \frac{1-\eta}{\eta} \right) W_t^{*(1-\eta)} \lambda_t W_t^\eta Lab_t^d + \beta \zeta_w \mathbb{E} \left( \frac{\pi_t^{\iota_w}}{\pi_{t+1}} \right)^{1-\eta} \mathbb{E} \left( \frac{W_{t+1}^*}{W_t^*} \right)^{\eta-1} f_{t+1} \\ f_t &= \varphi_t b_t \psi \mathbb{E} \left( \Pi_t^{*,w} \right)^{-\eta(1+\sigma_l)} Lab_t^{d(1+\sigma_l)} + \beta \zeta_w \mathbb{E} \left( \frac{\pi_t^{\iota_w}}{\pi_{t+1}} \right)^{-\eta(1+\sigma_l)} \mathbb{E} \left( \frac{W_{t+1}^*}{W_t^*} \right)^{\eta(1+\sigma_l)} f_{t+1} \end{aligned} \quad (28)$$

where

$$\Pi_t^{*,w} = \left( \frac{W_t^*}{W_t} \right) \quad (29)$$

and wages evolve according to:

$$1 = \zeta_w \left( \frac{(\pi_{t-1})^{\iota_w}}{\pi_t} \right)^{1-\eta} \left( \frac{W_{t-1}}{W_t} \right) + (1 - \zeta_w) \left( \Pi_t^{*,w} \right)^{1-\eta} \quad (30)$$

$Lab_t^d$  is labor demand. Aggregate labor supply is a function of wages and labor demand such that:

$$L_t = \int_0^1 \left( \frac{W_{j,t}}{W_t} \right)^{-\eta} dj Lab_t^d \quad (31)$$



## 2.3 Monetary Policy

I assume that the central bank targets core inflation,  $\pi_t^s$ , instead of aggregate inflation. The motivation for assuming core inflation targeting is both empirical and theoretical. Clark and Terry (2010) show that the Fed’s responsiveness to energy price shocks has decreased since 1985. Furthermore, Blinder and Reis (2005) and Mehra and Sawhney (2010) show that a Taylor-type rule with core inflation targeting tracks the observed policy rate better than with inflation targeting. Kara (2016) also finds that a Taylor-type rule with smaller weight on food and energy prices - relative to the weight implied by the CPI - better explains the Fed’s policy behaviour.

The theoretical motivation for core inflation targeting is found in Aoki (2001). Aoki shows that in an economy with flexible and sticky-price sectors it is optimal to target sticky-price inflation rather than aggregate inflation. Woodford (2016) observes that the results in Aoki (2001) provide the “theoretical basis for seeking to stabilise an appropriately defined measure of ‘core’ inflation rather than an equally weighted price index.” Equation (32) is the Taylor-type rule which targets core inflation and output growth in deviation from the steady-state:

$$\frac{R_t}{\bar{R}} = \left( \frac{R_{t-1}}{\bar{R}} \right)^{\rho_r} \left[ \left( \frac{\pi_t^s}{\bar{\pi}} \right)^{r_\pi} \left( \frac{Y_t}{\Lambda_z} \right)^{r_y} \right]^{1-\rho_r} m_t \quad (32)$$

where  $m_t$  is an exogenous shock and follows an AR(1) process.  $\bar{R}$  and  $\bar{\pi}$  are steady-state interest rate and inflation, respectively.  $\rho_r$ ,  $r_\pi$  and  $r_y$  are constant parameters.

## 2.4 Aggregation

Sector-specific capital, labor and output are aggregated according to:

$$\begin{aligned}
 K_t &= \left[ (\mu^u)^{\frac{1}{\theta}} (K_t^e)^{\frac{\theta-1}{\theta}} + (1 - \mu^u)^{\frac{1}{\theta}} (K_t^s)^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \\
 L_t &= \left[ (\mu^u)^{\frac{1}{\theta}} (L_t^e)^{\frac{\theta-1}{\theta}} + (1 - \mu^u)^{\frac{1}{\theta}} (L_t^s)^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \\
 Y_t &= \left[ (\Psi_y)^{\frac{1}{\theta}} (Y_t^e)^{\frac{\theta-1}{\theta}} + (1 - \Psi_y)^{\frac{1}{\theta}} (Y_t^s)^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}
 \end{aligned} \tag{33}$$

$Y_t$  is gross domestic output.  $\Psi_y$  is the weight on energy-sector output in GDP.<sup>7</sup>  $\mu^u$  is the weight on capital and labor dedicated to the energy goods sector. Finally, the resource constraint is defined as:

$$Y_t = C_t + I_t + a(u_t) \bar{K}_{t-1} \tag{34}$$

The rest of the aggregation is standard.

Most of the model variables are rescaled by  $z_t$  to generate variables constant in deterministic steady state. However, the rescaling of the following variables is done according to,  $\hat{r}_t = r_t \mu_t$ ,  $\hat{q}_t = q_t \mu_t$  and  $\hat{K}_t = \frac{K_t}{z_t \mu_t}$ .  $q_t$  is marginal Tobin's Q and equals the replacement cost of capital,  $q_t = \frac{1}{\mu_t}$ . It is further assumed that the cost of utilisation takes the following form:  $a(u_t) = \Phi_1(u_t - 1) + \frac{\Phi_2}{2}(u_t - 1)^2$ .

## 3 Calibration

I calibrate most of the model parameters according to estimation results in Fernandez-Villaverde (2010) (henceforth FV). FV takes a third-order Taylor-

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<sup>7</sup>In the rest of this paper, I assume that  $\Psi_y$  always takes the same value as the weight on energy goods in household consumption,  $\Psi$ . This approximation simplifies calibration. When households do not consume any energy goods (i.e.  $\Psi = 0$ ), all of GDP is made up of finished consumption goods.

approximation of the model solution similar to the models in Christiano et al. (2005) and Smets and Wouters (2007) and estimates the model using Bayesian estimation.<sup>8</sup>

When calibrating the model in this paper, I make two modifications to parameter estimates in FV. First, in line with Kara (2015) and Bils et al. (2012), I do not include price indexation in the model. Bils, Klenow and Malin find no evidence of price indexation in the micro-level data on prices. Instead, prices remain fixed for several periods. Second, consumption, in the FV model, is highly persistent with  $h$  equal to 0.97. I calibrate  $h$  to 0.6 which is closer to the rest of the literature (Christiano et al. (2005), Christiano et al. (2014) and Smets and Wouters (2007)). Reducing habit persistence increases the responsiveness of variables to energy price shocks.

The calibrated values for non-energy sector parameters are given in Table 1. These calibrations imply significant real and nominal rigidities. Significant habit persistence,  $h$ , and investment adjustment costs,  $\kappa$ , mean that both consumption and investment adjust gradually to exogenous shocks. This helps the model match the slow responses of macro variables in the empirical literature.

The values for  $\Lambda_a$  and  $\Lambda_\mu$  give a growth rate of 0.43% per quarter for the US economy. With standard deviations of  $\exp(-1.51)$  and  $\exp(-2.36)$ , respectively, the two preference shocks,  $b_t$  and  $\psi_t$ , are the most important of all shocks in the FV model. Finally, the parameters for the Taylor-rule suggest significant interest rate smoothing. The Fed follows the Taylor principle since the coefficient on inflation deviations is greater than 1,  $\rho_\pi = 1.29$ . However, with  $\rho_y = 0.19$ , there is only a

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<sup>8</sup>Different from Smets and Wouters (2007) and Christiano et al. (2005), FV further allows for a unit-root in productivity shock and an investment-specific technology shock.

Parameters	Values	Parameters	Values
$\delta$	0.025	$\epsilon$	10
$\eta$	10	$\Phi$	0
$\Phi_2$	0.001	$\beta$	0.998
$h$	0.60	$\psi$	8.92
$\sigma_l$	1.17	$\kappa$	9.51
$\alpha$	0.21	$\zeta_p$	0.82
$\zeta_w$	0.68	$\iota_w$	0.62
$r_y$	0.19	$r_\pi$	1.29
$\rho_r$	0.77	$\bar{\Pi}$	1.0
$\rho_b$	0.12	$\rho_\varphi$	0.93
$\sigma_b$	-1.51	$\sigma_\varphi$	-2.36
$\sigma_\mu$	-5.43	$\sigma_m$	-5.85
$\sigma_a$	-3.9	$\Lambda_a$	2.80E-03
$\Lambda_\mu$	3.40E-03		

**Table 1: Parameters for the Non-Energy Sector**

*Note: This table gives the calibrated values of the structural parameters in the model. The values are similar to Fernandez-Villaverde (2010) except for ‘h.’ Moreover, unlike in FV, the model does not include price indexation.*

small response to changes in the output growth gap.

Table 2 reports the values for energy sector parameters. The production and consumption shares of energy in output are targeted to equal 4.5% and 4%, respectively. The share of energy in production is obtained from the Use-table by commodities

Parameters	Values	Parameters	Values
$\mu$	0.053	$\Psi$	0.05
$\tau$	0.5	$\rho$	10
$\mu^u$	0.1	$\theta$	10
$\rho_\nu$	0.6	$\sigma_\nu$	-3.00

Table 2: **Parameters for the Energy Sector**

*Note: This table gives calibrated values of parameters governing the energy goods producing sector. The value for  $\Psi$  is calibrated to match the share of energy consumption in output of 4%. Whereas, the value for  $\mu$  is calibrated to match the share of energy in firms' production.*

provided by the Bureau of Economic Analysis.<sup>9</sup> To match the production share of 4.5%, I calibrate  $\mu$  to equal 0.053. The weight on energy goods in the consumption index,  $\Psi$ , is calibrated to match the share of energy consumption in output of 4%. Section 4 analyses how changes in the value of  $\Psi$  affect responses of macroeconomic variables to energy price shocks.<sup>10</sup> The targeted values for consumption and production shares of energy in output are closer to Dhawan and Jeske (2008).

The elasticity of substitution between energy and finished consumption goods,  $\tau$ , is less than one and is calibrated at 0.5. The assumption of complementarity between energy and finished consumption goods is standard in the literature (Dhawan and Jeske (2008)). The elasticity of substitution among differentiated energy goods,  $\rho$ , equals 10 which is similar to the finished goods sector.

I calibrate the energy shock process based on the stochastic volatility model estimated in Plante and Traum (2014). The stochastic volatility model helps in capturing important non-linearities in the data which are otherwise ignored in a linear

<sup>9</sup>To obtain the energy share in production, I sum the intermediate shares of oil and gas extraction, utilities and petroleum in U.S. GDP.

<sup>10</sup>In the model,  $\Psi$  determines the share of energy consumption in output. As  $\Psi$  increases, the share of energy consumption in output also increases.

AR(1) model (Fernandez-Villaverde and Rubio-Ramirez (2010)). The persistence parameter for the energy shock in the model is calibrated at 0.6. I assume relatively low energy price uncertainty in the baseline specification. Therefore, the standard deviation of energy price shocks,  $exp(\sigma_\nu)$ , is calibrated to 0.05 which is half of the estimate in Plante and Traum.

## 4 Results

The parameter values in section 3 represent the baseline calibration. In this section, I first explain how changes in the share of energy in household consumption affects firms' responsiveness to energy price shocks. In doing so, I keep the share of energy in firms' production as fixed. Therefore, a change in the share of energy in households' consumption can be interpreted as a relative change in the consumption share of energy goods.

In the second part, I discuss the effect of an energy price shock on core inflation when uncertainty about energy prices varies from low to high. I refer to the baseline specification as a low uncertainty environment. In the contrasting high uncertainty environment, the standard deviation of the energy price shock is increased from 0.05 to 0.35. However, unlike in the literature on the effect of volatility or uncertainty shocks, the standard deviation of the shock is held constant in each environment. This allows to study the effect of a level shock under different uncertainty environments.<sup>11</sup>

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<sup>11</sup>The decision rules are approximated up-to third-order Taylor expansion. I use Dynare 4.4.3 to implement this.

## 4.1 Consumption Channel and Energy Price Uncertainty

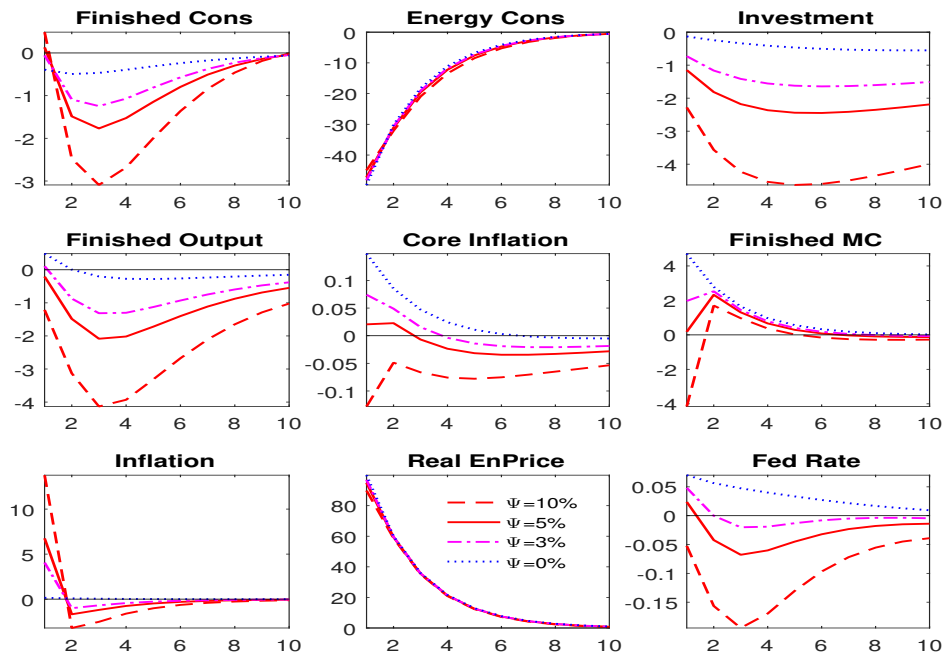


Figure 1: IRFs Under Different Consumption Shares

The blue dotted line plots the impulse responses to an energy price shock when households do not consume energy goods. The magenta dotted-dashed line plots the IRFs to an energy price shock when the share of energy in households' consumption is 3%. The red solid line plots the IRFs to an energy price shock when the share of energy in households' consumption is 5%. The red dashed line plots the IRFs to an energy price shock when the share of energy in households' consumption is 10%.

To understand key results, I will first explain the two important channels in the model - the production channel and the consumption channel. An increase in the energy price puts upward pressure on core inflation. This is because finished-goods producing firms use energy goods as an additional factor input to produce finished consumption goods. As a result, an increase in the energy price increases firms

marginal costs (see eq. 18). This is the production channel. On the other hand, since households consume energy goods, a positive energy price shock also decreases households' purchasing power. This puts downward pressure on core inflation. I refer to this as the deflationary effect of an energy price shock.

The results show that core inflation dynamics, following a positive energy price shock, depend on which of the two channels is more important in the model. When the relative importance of the households' sector in energy consumption increases, the deflationary effect of an energy price shock increases. Figure 1 plots impulse responses to a positive energy price shock when the weight on energy goods in households' consumption is 0%, 3%, 5% and 10%. In the absence of households' consumption of energy goods ( $\Psi = 0\%$ ), core inflation always increases in response to a positive energy price shock. However, as the relative share of energy in households' consumption increases, the deflationary effect of an energy price shock starts to dominate. Core inflation increases less following an identical increase in real energy prices. When the relative share is large enough, firms no longer increase their prices in response to an energy price shock. Instead, since firms cannot adjust their prices every period, firms decrease their prices in expectation of a reduction in households' demand for finished consumption goods.

Energy price uncertainty further amplifies the deflationary effect of energy price shock. Figure 2 plots third-order impulse responses, in terms of percentage deviation from the steady state, to a 100% increase in the energy price when energy price uncertainty is low, medium and high.<sup>12</sup> When energy prices are more uncertain,

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<sup>12</sup>The results are robust to even a much smaller increase in energy prices.



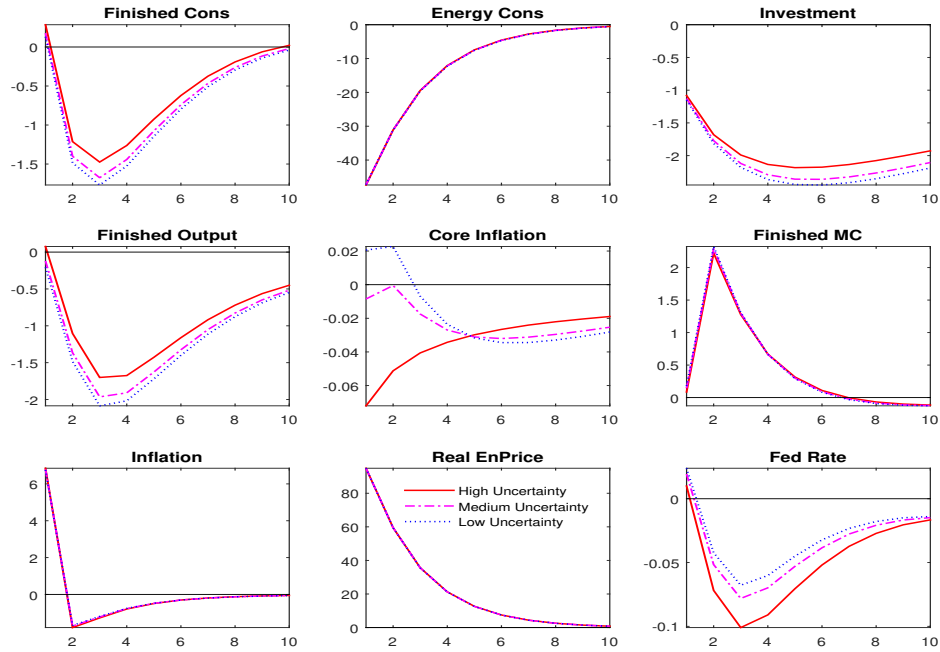


Figure 2: **Deflationary Effect of Energy Price Shock as Uncertainty Increases**

*The blue dotted line plots the impulse responses to an energy price shock when energy prices are relatively certain. The maganta dotted-dashed line plots the IRFs to an energy price shock when energy prices are relatively uncertain. The red solid line plots the IRFs to an energy price shock when energy prices are highly uncertain.*

firms increase their prices by less following a positive energy price shock. In an environment with highly uncertain energy prices, firms respond by increasing their prices by significantly less such that core inflation falls below its steady-state at the time of shock.

I now turn to explaining the reason behind amplification of the deflationary effect.

### 4.1.1 Upward Pricing Bias Channel

Fernandez-Villaverde et al. (2015) explain the role of upward pricing bias channel in the context of fiscal volatility shocks. As shown in Fernandez-Villaverde et al. (2015), the profit function of firms is asymmetric such that losses are higher when firm's price relative to its competitors is lower than when it is higher. Since prices are sticky, price setting firms bias their prices upwards when setting their optimal price. When uncertainty about future price level is higher, magnitude of the pricing bias increases.

Upward pricing bias can also be imagined as a form of self-insurance against future cost shocks. This has an obvious implication. When a positive cost shock hits the economy, firms require a smaller increase in their prices than they would have in absence of the upward pricing bias. This point is further explained in section 4.2.

Equation (36) and equation (37) are the corresponding third-order approximations of the decision rule for core inflation when the energy price uncertainty envi-

ronment changes from low to high, respectively:<sup>13</sup>

$$\begin{aligned} \hat{\pi}_t^s = & 0.000236 - 0.076350\hat{R}_{t-1} + 0.001027\hat{p}_{t-1}^{e*} + 0.122568\hat{I}_{t-1} + \dots \\ & + 0.000478\epsilon_{\nu,t} + \dots + G_2^{\pi^s}(\hat{z}_t \otimes \hat{z}_t) + G_3^{\pi^s}(\hat{z}_t \otimes \hat{z}_t \otimes \hat{z}_t) \end{aligned} \quad (36)$$

The first term on the right hand side of both equations (i.e. the constant) captures the upward pricing bias in firms pricing decision. Equation (36) shows that when uncertainty about energy prices is low, the magnitude of upward pricing bias is relatively smaller. Moreover, a positive energy price shock increases core inflation above its steady-state.

$$\begin{aligned} \hat{\pi}_t^s = & 0.009839 - 0.042360\hat{R}_{t-1} - 0.000640\hat{p}_{t-1}^{e*} + 0.097148\hat{I}_{t-1} + \dots \\ & - 0.000550\epsilon_{\nu,t} + \dots + G_2^{\pi^s}(\hat{z}_t \otimes \hat{z}_t) + G_3^{\pi^s}(\hat{z}_t \otimes \hat{z}_t \otimes \hat{z}_t) \end{aligned} \quad (37)$$

On the other hand, in a high uncertainty environment, the magnitude of pricing bias increases out of precaution. Higher precautionary markups insure the price setting firm against future states where shocks to the economy will lower the price of a firm relative to her competitors.

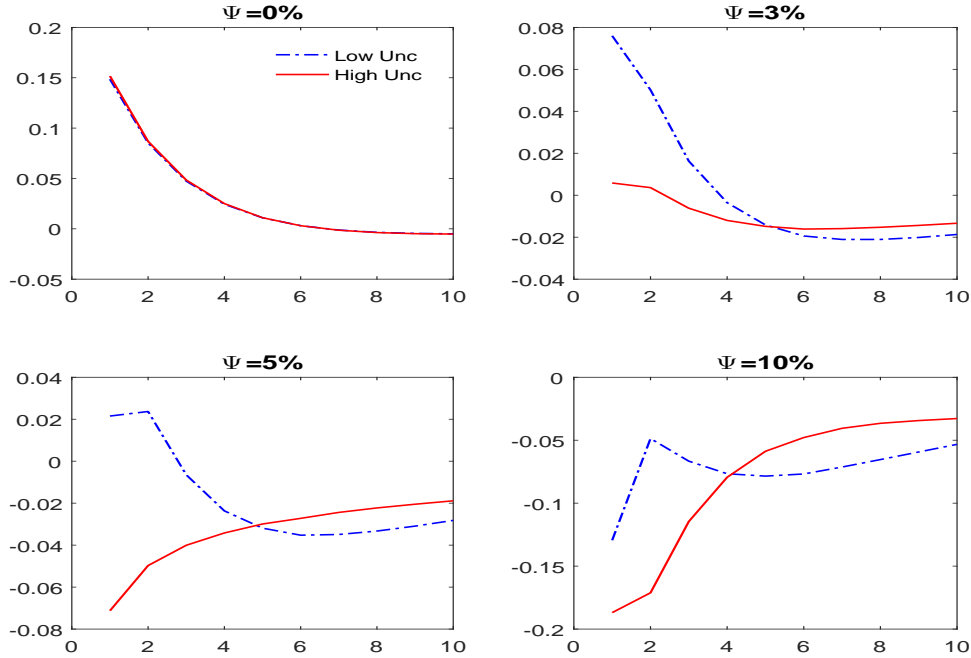
For the results in this paper, when a positive energy price shock hits the economy, precautionary markups provide a cushion against the shock. As a result, firms require

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<sup>13</sup>The decision rules are expressed in the form adopted by Dynare (Reference Manual Version 4, Ch. 4, pg. 48) as in equation (35):

$$\hat{y}_t = G_0 + G_1\hat{z}_t + G_2(\hat{z}_t \otimes \hat{z}_t) + G_3(\hat{z}_t \otimes \hat{z}_t \otimes \hat{z}_t) \quad (35)$$

where  $\hat{y}_t$  is a column vector of endogenous variables in the model and is written in terms of deviation from the steady-state.  $\hat{z}_t$  is a vector of state variables at date 't - 1' in terms of deviation from their steady-state.  $\hat{z}_t$  also includes the exogenous shocks.  $G_0, G_1, G_2$  and  $G_3$  are matrices where the elements of each matrix are complex functions of structural parameters of the model. Since the standard deviation of energy price shocks does not affect matrices  $G_2$  and  $G_3$ , I only expand matrix  $G_0$  and  $G_1$  for core inflation (i.e.  $\pi_t^s$ ) in equation (36) and (37).



**Figure 3: Core Inflation Responses when Consumption Share Increases and Energy Prices Become More Uncertain**

*Each subplot plots the IRFs for core inflation in response to an energy price shock when the share of energy in households' consumption is 0%, 3%, 5% and 10%, respectively. Within each subplot, the blue dotted-dashed line is the IRF when energy prices are certain and the red solid line is the IRF when energy prices are highly uncertain.*

a smaller increase in their prices. When precautionary markups are significantly higher, as in equation (37), firms increase their prices only marginally such that core inflation moves below its steady-state.

Figure 3 shows that upward pricing bias channel in this model operates through aggregate prices. Since energy prices are also consumed by the households, higher energy price uncertainty makes aggregate price level more uncertain as well. Higher uncertainty about expected prices causes firms to bias their prices upwards even

more. This is because higher uncertainty increases the probability that future prices will be further from their expected value. Since losses are higher if firm's price is lower relative to her competitors than if it is higher, magnitude of precautionary markups increase. In contrast, when energy goods are not consumed by households (i.e.  $\Psi = 0$ ), aggregate price level does not depend on energy prices. As a result, higher energy price uncertainty does not directly affect uncertainty about aggregate price level. This closes the upward pricing bias channel in the model. Consequently, core inflation dynamics in response to the shock no longer depend on energy price uncertainty. But as the weight on energy prices in aggregate price index increases, high energy price uncertainty starts to amplify the deflationary effect of energy price shocks.

However,  $\Psi$  also determines the share of energy in households consumption. This raises the possibility that amplification of the deflationary effect - attributed to the upward pricing bias channel in this section- is driven by how households respond to energy price shocks under high uncertainty environment. Section 4.1.2 explores this possibility and shows that this is not the case.

#### **4.1.2 Precautionary Savings Motive of Households**

The decision rules for finished goods consumption show that higher energy price uncertainty increases households' precautionary savings motive.<sup>14</sup> In this section, I study how changes in precautionary savings motive affect households' consumption behavior in response to an energy price shock. At the same time, I keep the degree

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<sup>14</sup>I do not report the decision rules for brevity.

of energy price uncertainty fixed.

To see how households' precautionary savings motive affect their consumption behavior, while keeping energy price uncertainty fixed, I replace the utility function in equation (22) with equation (38):

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t b_t \left[ \frac{C_{j,t}^{1-\gamma}}{1-\gamma} - \varphi_t \psi \frac{L_{j,t}^{1+\sigma_l}}{1+\sigma_l} \right] \quad (38)$$

where  $\gamma$  determines the curvature of households' utility function. A higher value for  $\gamma$  increases the curvature and, therefore, makes households' more risk averse. Furthermore, to simplify analysis, I also abstract from habits throughout this section.

Higher risk aversion has important implication for households' consumption behavior. As  $\gamma$  increases, households increase their precautionary savings in order to self-insure against adverse shocks. This has an opposite effect on core inflation than what is required to explain amplification of the deflationary effect of energy price shocks. When a positive energy price shock hits the economy, households use their precautionary savings to dampen the contractionary effect of energy price shock on consumption. As a result, consumption falls less. Higher precautionary savings lead to an even smaller contraction in consumption. These results suggest that, instead of amplifying, households' precautionary savings motive work towards dampening the deflationary effect of energy price shock under high uncertainty environment.

Figure 4 and figure 5 plot impulse responses to an energy price shock when  $\gamma$  equals 4 and 2, respectively, and energy prices are highly uncertain. Both figures also include impulse responses for first, second and third-order Taylor-approximation of the model solution. It is important to note that the effect of precautionary savings is captured at second-order, whereas most of the effect of energy price uncertainty is

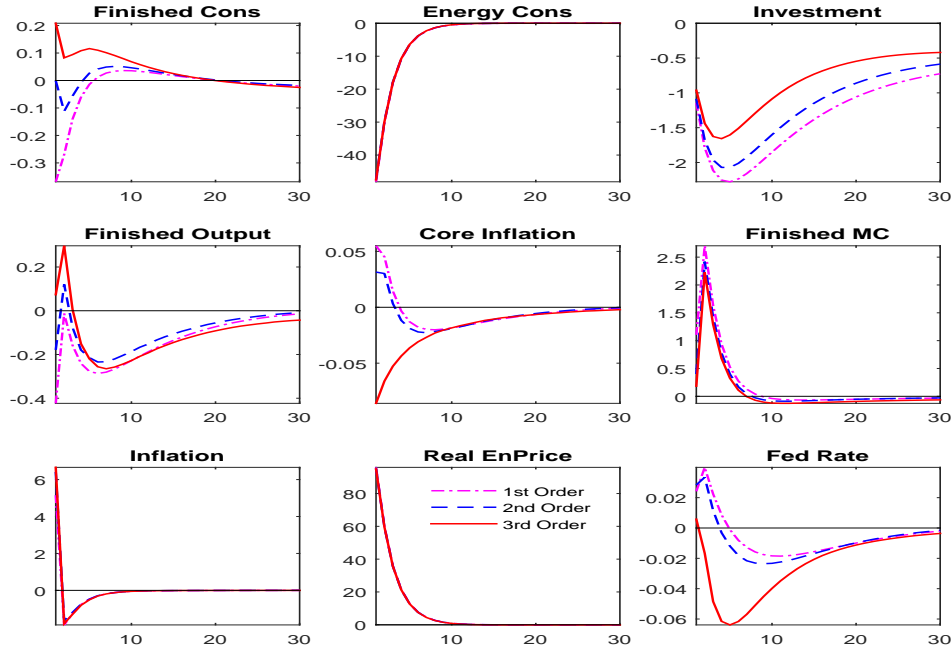


Figure 4: **Impulse Responses under Higher Risk Aversion**

*This figure plots impulse responses to energy price shock when energy price uncertainty is high and  $\gamma$  equals 4. The figure plots IRFs for 1st, 2nd and 3rd-order Taylor-approximation of the model solution.*

captured at third-order.<sup>15</sup> Therefore, comparing second-order impulse responses with first-order responses for each  $\gamma$  will highlight how precautionary savings motive affects households' consumption behavior in response to an energy price shock. Similarly, comparing third-order responses with second-order responses will highlight the role of energy price uncertainty.

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<sup>15</sup>I also do a similar exercise when energy price uncertainty is low. I find that second and third-order responses for finished goods consumption are similar. This confirms that the effect of households' degree of risk aversion,  $\gamma$ , on finished goods consumption is fully captured at second-order. Therefore, it is safe to say that any differences between second and third-order responses are due to energy price uncertainty rather than households' risk aversion. I do not report the impulse responses under low energy price uncertainty for brevity.

It is also worth highlighting what I do not do. I do not compare the *level* of responses across the two figures. This is because, in a model with expected utility,  $\gamma$  also determines the degree of intertemporal elasticity of substitution (i.e.  $IES=1/\gamma$ ). This means that changing the value for  $\gamma$  also affects resulting dynamics through changes in IES. Lower IES means that households' willingness to smooth consumption is higher than when IES is higher. As a result, consumption contracts less in figure 4 than in figure 5. This shows that changes in IES has significant first-order effect. To abstract from the effect of changes in IES, instead of comparing *levels*, I compare the differences between second and first-order responses across the two figures when discussing the implication of households' precautionary savings motive for finished goods consumption.<sup>16</sup>

Figure 4 shows that the contractionary effect of an energy price shock is significantly smaller at second-order than at first-order. This is because higher precautionary savings provide a cushion against the energy price shock thus allowing households to decrease their consumption of finished goods by less. As a result, the contractionary effect of energy price shock decreases. Core inflation responses are almost similar at both first and second-order. However, at third-order, core inflation falls below its steady-state. I also do a similar exercise for lower degree of risk aversion. Figure 5 plots impulse responses when  $\gamma$  equals 2. Lower risk aversion decreases households' precautionary savings motive. As a result, unlike under large degree of risk aversion, first and second-order responses for finished consumption

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<sup>16</sup>Ideally, one should use recursive preferences (e.g. Epstein-Zin preferences) to study the effect of changes in risk aversion. Epstein-Zin preferences allow to change the degree of risk aversion without changing IES. However, this is not easy to implement in this model where there are two consumption goods. I leave this for future research.



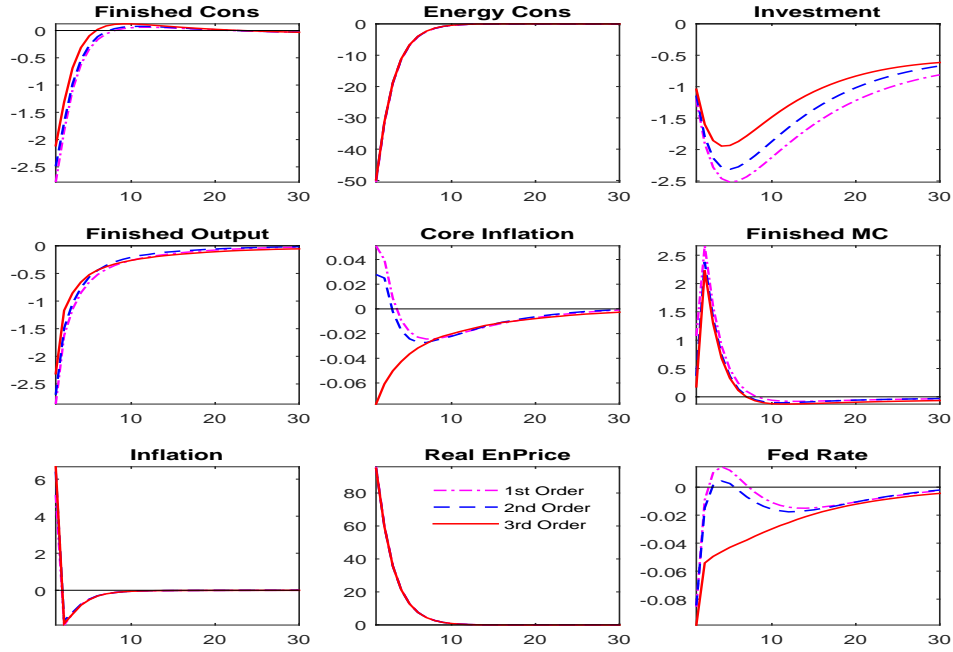


Figure 5: **Impulse Responses under Lower Risk Aversion**

*This figure plots impulse responses to energy price shock when energy price uncertainty is high and  $\gamma$  equals 2. The figure plots IRFs for 1st, 2nd and 3rd-order Taylor-approximation of the model solution.*

goods become similar. However, core inflation responses are almost similar to when  $\gamma$  was equal to 4. This suggests that core inflation dynamics in response to an energy price shock cannot be explained by how households respond to higher energy price uncertainty.

Note that the contractionary effect of energy price shock on finished goods consumption dampens further at third-order. It is completely offset when  $\gamma$  equals 4. This could be due to several reasons. Firstly, as mentioned earlier, increase in energy price uncertainty also works towards increasing households precautionary sav-

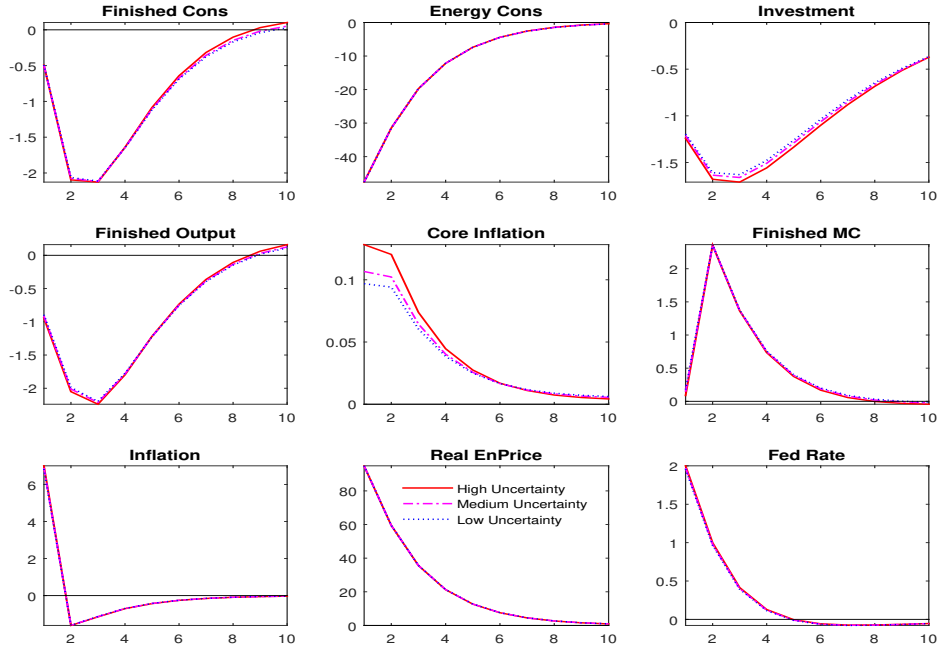
ings motive. An additional increase in precautionary savings can, therefore, further dampen the contractionary effect of energy price shock on finished goods consumption. Secondly, a smaller increase in finished goods prices means that households' purchasing power decreases by less. As a result, finished goods consumption also decreases less. Lastly, an expansionary monetary policy can encourage households to substitute tomorrow's consumption for today's consumption. Nonetheless, all three reasons work towards dampening the contractionary effect on households' consumption and, therefore, cannot explain why higher energy price uncertainty amplifies the deflationary effect of energy price shock.

These results confirm that households' consumption behavior, following an energy price shock, cannot be an adequate explanation of why higher energy price uncertainty amplifies the deflationary effect of energy price shocks.

## 4.2 Inflation Targeting Regime and Core Inflation

This section discusses dynamics of core inflation when the FED explicitly responds to energy prices through inflation targeting. When the FED targets aggregate inflation instead of core inflation in equation (32), a positive energy price shock only leads to an above-trend core inflation. Figure 6 plots the corresponding impulse responses to an energy price shock under different uncertainty environments. Core inflation increases at the time of shock and then returns to its steady-state. Unlike in figure 2, an energy price shock no longer leads to a below trend core inflation as uncertainty increases.

The intuition for this result is as follows. When the central bank targets aggregate



**Figure 6: Impulse Responses under Inflation Targeting Regime**  
*This figure plots impulse responses when the FED targets aggregate inflation. The blue dotted line plots the IRFs to an energy price shock when energy prices are relatively certain. The maganta dotted-dashed line plots the IRFs to an energy price shock when energy prices are relatively uncertain. The red solid line plots the IRFs to an energy price shock when energy prices are highly uncertain.*

inflation, aggregate price level is less uncertain. As a result, explicit monetary policy response to energy prices ameliorates the effect of the upward pricing bias channel discussed in section 4.1.1. This is because, since firms are now more certain about expected price level, they do not require precautionary markups when setting their prices. However, lack of precautionary markups mean that, when a positive energy price shock hits the economy, price setting firms will have to increase their prices by significantly more than they would have in the presence of precautionary markups.

An aggressive monetary policy response, however, leads to a significant increase in interest rate and therefore a greater contraction in output and finished goods consumption. However, since firms are now more certain about expected price level, investment declines less and recovers faster than under core inflation targeting. Consequently, finished sector output also recovers faster. Both finished goods consumption and finished sector output recovers in less than ten quarters.

#### 4.2.1 Decision Rules

Equation (39) and equation (40) are the corresponding decision rules under low and high uncertainty, respectively, when the FED targets aggregate inflation:

$$\begin{aligned} \hat{\pi}_t^s = & 0.000014 - 0.077920\hat{R}_{t-1} + 0.003136\hat{p}_{t-1}^{e*} + 0.123400\hat{I}_{t-1} + \dots \\ & + 0.001732\epsilon_{\nu,t} + \dots + G_2^{\pi^s}(\hat{z}_t \otimes \hat{z}_t) + G_3^{\pi^s}(\hat{z}_t \otimes \hat{z}_t \otimes \hat{z}_t) \quad (39) \end{aligned}$$

The constants on the right hand side of both equations show that the upward pricing bias channel is significantly dampened when compared with corresponding decision rules under core inflation targeting (i.e. eq. (36) and eq. (37)).

$$\begin{aligned} \hat{\pi}_t^s = & -0.002370 - 0.083360\hat{R}_{t-1} + 0.003699\hat{p}_{t-1}^{e*} + 0.128187\hat{I}_{t-1} + \dots \\ & + 0.002142\epsilon_{\nu,t-1} + \dots + G_2^{\pi^s}(\hat{z}_t \otimes \hat{z}_t) + G_3^{\pi^s}(\hat{z}_t \otimes \hat{z}_t \otimes \hat{z}_t) \quad (40) \end{aligned}$$

Precautionary markups are completely eliminated in equation (40). This is because, as uncertainty about energy prices increase, monetary policy reacts more to stabilise inflation.<sup>17</sup> Consequently, as explained before, firms become more responsive to

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<sup>17</sup>A similar comparison of decision rules for interest rate suggests that interest rate responds more to changes in inflation when uncertainty is high. On the other hand, under core inflation targeting, interest rate responds less to changes in inflation when uncertainty is high. I do not

energy price shocks. Firms' responsiveness to energy price shocks increases further when energy prices are highly uncertain. Additionally, core inflation also responds more to other state variables in the model.

These results further confirm that the channel through which higher energy price uncertainty affects core inflation dynamics is the upward pricing bias channel.

## 5 Sensitivity to Structural Parameters

The results in section 4 are strongly dependent on the degree of nominal rigidities in the model. When prices are fully flexible, all firms revise their prices upwards as marginal cost increases. A sharp increase in core inflation results in an even greater decrease in households' consumption and, therefore, output. Later, when the marginal cost returns to its steady-state, firms decrease their prices in the face of economic contraction. The ability to reset prices every period means that firms do not require precautionary markups when setting their price. As a result, the upward pricing bias channel disappears.

In contrast, when wages are fully flexible, core inflation decreases at the time of the shock even in a low uncertainty environment. This is because, under flexible wages, households can revise their wages downwards as the contraction in the economy increases. Therefore, marginal cost returns to its steady-state relatively quickly. Since prices are sticky and the increase in marginal costs is less persistent, firms revise their prices downwards when they expect output to stay below its steady-state for a longer period.

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report the corresponding decision rules for brevity.

I also consider how results in this paper change when energy and finished goods are substitutes rather than compliments. When  $\tau$  is calibrated to equal 1.5, finished goods consumption increases. This is because households substitute energy goods for finished consumption goods. Since finished goods consumption and finished output increases, core inflation increases following a positive energy price shock.

Finally, a decrease in product differentiation across finished goods producing firms further amplifies the deflationary effect of a positive energy price shock. As elasticity of substitution between intermediate finished goods,  $\epsilon$ , increases, core inflation decreases even more. On the other hand, a lower  $\epsilon$  leads to finished goods firms increasing their prices even when energy prices are highly uncertain. Nonetheless, for any given value for  $\epsilon$ , higher energy price uncertainty dampens the inflationary effect of an energy price shock.

## 6 Conclusion

Recent empirical evidence suggests that the pass-through from energy prices to both aggregate inflation and core inflation has decreased since the 1980s. However, there are only few papers which attempt to provide a structural explanation for this observed decrease in energy price pass-through. Blanchard and Gali (2010) use a New Keynesian model to study why the pass-through has decreased from energy prices to aggregate inflation. This paper focuses on energy price pass-through to core inflation. I extend a standard New Keynesian model to allow for domestic production of energy goods which are then consumed both by finished goods producing firms

and households. I then use the new model to show how an increase in the relative share of energy in households' consumption together with uncertain energy prices can provide an explanation for the decrease in pass-through to core inflation.

In the new model, energy goods are consumed by both finished goods producing firms and the households. As a result, an increase in the energy price not only increases firms' marginal cost but also decreases households' demand for finished consumption goods. Whether firms will increase their prices in response to a positive energy price shock depends on the relative importance of each of these two channels. When the share of energy in households' consumption is relatively low, the inflationary effect of an energy price shock will dominate. However, as the relative share of energy in households' consumption increases, the deflationary effect of an energy price shock starts to dominate.

The deflationary effect explained above is further amplified when energy prices are highly uncertain. This is due to the upward pricing bias in firms' pricing decision (Fernandez-Villaverde et al. (2015)). Energy price uncertainty makes expected prices more uncertain. Since price setting firms cannot adjust their prices every period, they bias their prices upwards. Allowing for precautionary markups insures firms against expected cost shocks. As a result, when a positive cost shock hits the economy, firms require a smaller increase in their prices than in absence of the pricing bias. When energy prices and, therefore, expected price level is highly uncertain, the magnitude of the bias increases. Consequently, following an energy price shock, firms require an even smaller increase in their prices. This provides an explanation for why energy price uncertainty amplifies the deflationary effect of energy price shocks.

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