Modeling the Asymmetric Effects of an Oil Price Shock*

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Abstract

Hamilton (1996, 2003, 2011) asserts in his "net oil price increase" (NOPI) model that a rise in oil prices generates a larger decline in output when the oil price hits a near-term high relative to its recent history. This paper develops a New Keynesian model with energy and a downward nominal wage rigidity that generates results consistent with the stylized facts of the NOPI model. Specifically, we show a large energy price increase pushes down the real wage enough that the downward nominal wage constraint binds for several periods, which causes firms to further reduce their output. Since that mechanism is unimportant when energy prices fall, the downward nominal wage constraint causes output to react asymmetrically to oil price shocks. We demonstrate how output's asymmetric response depends on the labor supply elasticity, the amount of price stickiness, the steady-state inflation rate, and the degree of downward nominal wage rigidity.

Keywords: Energy shocks; Downward nominal wage rigidity; Asymmetry; Nonlinear; Net oil price increase

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1 Introduction

Many empirical studies have documented that oil price shocks have a negative effect on output.[1] One key finding in the literature is models that allow for asymmetry or another form of nonlinearity fit the data better and provide superior forecasts compared with linear VAR models. Two of the most popular specifications are Hamilton's (1996, 2003, 2011) "net oil price increase" (NOPI) model and Kilian and Vigfusson's (2013) "net oil price change" model. The NOPI model predicts that a rise in oil prices generates a larger decline in output when the price of oil hits a near-term high relative to its recent history.[2] The net oil price change model, in contrast, implies that a change in oil prices generates a larger shift in output when the price of oil hits a near-term high or near-term low. Previous theoretical research can be used to motivate nonlinear empirical specifications, but those theoretical models cannot generate the asymmetric responses of output consistent with either the NOPI model or the net oil price change model. This paper documents the stylized facts of the NOPI model and then develops a New Keynesian model with energy that produces impulse responses consistent with Hamilton's (1996, 2003, 2011) NOPI model.

A few theoretical models have been used to motivate the asymmetric responses of output to oil price changes. Bernanke (1983) suggests that agents reduce their irreversible investment whenever an exogenous shock, like a large oil price change, increases economic uncertainty. The asymmetry in that framework, however, depends on the uncertainty generated by the price change and not the direction of change. Hamilton (1988) argues capital and labor can not costlessly move from the sectors that experience a decline in demand to sectors that experience a rise in demand. That lack of mobility means output definitely will fall after an oil price increase and may even fall after an oil price decrease (Hamilton 2003).

[1] For reviews of the early literature, see Hamilton (2008) and Kilian (2008). A few recent contributions include Kilian (2009), Hamilton (2011), Kilian and Vega (2011), and Aastveit (2014). Papers that have worked with theoretical models of the effects of oil shocks similar to this paper include Bodenstein, Erceg, and Guerrieri (2008), Dhawan and Jeske (2008), Blanchard and Gali (2009), Dhawan, Jeske, and Silos (2010), Blanchard and Riggi (2013), Bodenstein, et al. (2013), Plante (2014), Gavin, Keen, and Kydland (2015), and Balke and Brown (2018).

[2] Hamilton (2003) finds comparison with the previous three years is the best choice.

Although Mork (1989) finds some empirical support for Hamilton's (1988) costly reallocation of resources argument, Herrera, Lagalo, and Wada (2011) and Kilian and Vigfusson (2011) find Hamilton's (1988) theoretical explanation inconsistent with asymmetries observed in the data. Wei (2003) uses a general equilibrium model with putty-clay investment to show higher oil prices amplify the decline in output by making some capital obsolete. The putty-clay model, however, does not allow substitutability of factors of production once capital is installed, which means Wei's (2003) specification has some of the characteristics of Hamilton's (1988) costly reallocation of resources model.

We begin by documenting the asymmetric effects of an oil price shock using the NOPI model, showing that a net oil price increase generates a larger decline in output than a similar-sized oil price increase that does not reach a near-term high. A net oil price increase also impacts the labor market by generating higher nominal wages and reducing hours worked. As with the goods market, consumption, business fixed investment, and nonresidential investment all decline more rapidly following a net oil price increase compared with a non-net oil price increase.

This paper develops a New Keynesian model with downward rigid nominal wages to account for the asymmetric effects in the goods and labor markets from an energy price increase.[3] In our model, energy is both an input in the production function and a consumption good, where the constraint preventing nominal wages from falling is the key friction needed to generate asymmetric effects from an energy price shock. Specifically, downward rigid nominal wages enhance the decline in output after a large energy price increase by preventing the nominal wage from falling. The increase in energy prices drives up production costs, which causes firms to reduce their demand for labor. The higher energy costs also decrease households' demand for energy, consumption, and investment, but they increase households' supply of labor. The increase in labor supply combined with the reduction in labor demand

[3]The empirical literature on downward rigid nominal wages includes Gottschalk (2005), Barattieri, Basu, and Gottschalk (2014), and Hazell and Taska (2018), while the theoretical literature includes Kim and Ruge-Murcia (2009, 2011), Benigno and Ricci (2011), Abo-Zaid (2013), Schmitt-Grohe and Uribe (2016), and Baqaee (2018).

puts downward pressure on real and nominal wages. If the pressure is strong enough, the nominal wage hits its downward constraint and is unable to decline any more. Firms then respond by further reducing their labor demand and output by more than they would in a flexible-wage economy. As a result, a New Keynesian model with downward rigid nominal wages generates asymmetric effects after an energy price increase similar to the asymmetry observed in the data. Finally, we conduct a sensitivity analysis that shows our results depend critically on the calibration of certain parameters of the model.

The paper proceeds as follows. Section 2 describes the data, methodology, and impulse response functions for key economic variables after an oil price shock in both the linear model and the nonlinear NOPI model. Section 3 presents our theoretical model. Section 4 discusses the calibration of the theoretical model and the solution techniques utilized to generate the rational expectations solution. Section 5 displays the model's impulse response functions to an energy price increase and decrease, illustrates the decision rules associated with various sizes of energy price shocks, examines the robustness of our results to alternative calibrations of key model parameters, and discusses the differences in the effects of an energy price shock caused by foreign demand and foreign supply shocks. Section 6 concludes.

2 Stylized Facts

This section documents some of the stylized facts of Hamilton's (1996, 2003, 2011) NOPI model that any plausible theoretical model of the transmission of oil price shocks to the macroeconomy should be able to replicate. We show the economy responds more strongly to oil price shocks in the NOPI time periods than in the non-NOPI time periods.[4] That is, oil price shocks have a greater effect on key economic variables when the price of oil reaches

[4] A partial list of papers that have worked with the NOPI model includes Bernanke, Gertler, and Watson (1997), Balke, Brown, and Yucel (2002), Lee and Ni (2002), Cunado and de Gracia (2003), Herrera, Lagalo, and Wada (2011), and Ravazzolo and Rothman (2013). Acceptance of the NOPI model has not been universal among macroeconomists (e.g., see Kilian and Vigfusson (2011, 2013, 2017)). Kilian and Vigfusson (2011) conclude that "most of the time the linear symmetric model provides a good approximation in modeling the responses of real output to innovations in the real price of oil."

new highs relative to its recent history. Following Hamilton (2003), $NOPI_t$ is defined to be the larger of zero or the percentage difference between the log of the current oil price, oil_t, and the log of the highest oil price of the previous three years, $\widetilde{oil}_t$:

$$NOPI_t = max\left(0, oil_t - \widetilde{oil}_t\right). \tag{1}$$

The economy is considered to be in the NOPI regime if $NOPI_t > 0$ and in the non-NOPI regime if $NOPI_t = 0$.

We examine the nonlinear relationship between the price of oil and the macroeconomy by calculating the differences in the responses of the economy to an oil price shock that occurs in the NOPI and non-NOPI regimes. If a linear model is a good approximation of the economy's response to an oil price shock, then the responses in the NOPI and non-NOPI regimes will be effectively the same. A large difference in those responses, however, indicates the economy's response to an oil price shock is strongly nonlinear. In that case, any theoretical macroeconomic model that does not account for that nonlinearity should be discounted, particularly as a tool to guide monetary policy's response to oil price shocks.

Oil price shocks in Hamilton's (1996, 2003, 2011) NOPI model can be summarized in one of three ways: 1) An increase in the oil price of $x\%$ when the economy is in the NOPI regime (Shock 1); 2) An increase in the oil price of $x\%$ when the economy is in the non-NOPI regime (Shock 2); and 3) A decrease in the oil price of $x\%$ when the economy is in the non-NOPI regime (Shock 3). If the response to an oil price shock is linear, those three shocks have economic effects that are of the same magnitude, but not necessarily of the same sign. A comparison of the effects of Shock 1 against the effects of Shock 2 is appropriate if, as in Kilian and Vigfusson (2011), the experiment is focused on the nonlinear responses of the macroeconomy to oil price increases. That comparison, however, is not the only way to examine the nonlinear effects of oil price shocks, and it may not be the best comparison in all situations.

Our objective is to assess the differences in the economic effects of an oil price shock in the NOPI and non-NOPI regimes. We compare the effects of an oil price increase in the NOPI regime, Shock 1, to those of an oil price decrease in the non-NOPI regime, Shock 3. That comparison provides a valid measure of the difference in the behavior of the economy across the NOPI and non-NOPI regimes. One might be tempted to equate an oil price increase in the non-NOPI regime, Shock 2, with an oil price decrease in the non-NOPI regime, Shock 3, but the two shocks are not equivalent. Depending on the size of the oil price shock and the recent history of the price of oil, an oil price increase in the non-NOPI regime may be large enough to push the economy into the NOPI regime. In that case, the responses to Shock 2 will not be symmetric to the responses to Shock 3, and instead, will be equal to the responses to Shock 1. Averaging over all possible states of the economy that can be observed in the non-NOPI regime, responses to Shock 2 will be somewhere between responses to Shock 1 and responses to Shock 3.

That observation has two important implications for our analysis. One, comparing the economic effects of an oil price increase in the NOPI regime, Shock 1, with an oil price increase in the non-NOPI regime, Shock 2, is a biased measure of the difference between the NOPI and non-NOPI regimes. Two, even though a comparison of economic effects of Shock 1 against Shock 2 provides a valid test of the null hypothesis of linearity, the test by construction is less powerful than the equally valid comparison of economic effects of Shock 1 against Shock 3. Therefore, we compare the economic effects of an oil price increase in the NOPI regime, Shock 1, with the economic effects of an oil price decrease in the non-NOPI regime, Shock 3.

2.1 Methodology

To assess the impact of economic shocks on key variables, economists often estimate a linear VAR model and then use those estimates to calculate the relevant impulse response functions. The NOPI model, however, cannot be estimated using a linear VAR model because the variable $NOPI_t$ is a nonlinear transformation of the price of oil (e.g., see Hamilton 2011, Kilian and Vigfusson 2011, 2013). To estimate the nonlinear NOPI model, we use the method of local projections introduced by Jorda (2005). Unlike linear VAR models, nonlinear models will generate impulse response functions that are dependent on the size and sign of the oil price shock. Our analysis focuses on comparing the impulse response functions for a 10% oil price increase in the NOPI regime ($\Delta oil_0^{NOPI} = 0.10$ and $NOPI_0^{NOPI} = 0.10$) to the impulse response functions for a 10% oil price decrease in the non-NOPI regime ($\Delta oil_0^{non-NOPI} = -0.10$ and $NOPI_0^{non-NOPI} = 0$).

Kilian (2009) and Kilian and Vega (2011) present strong evidence that oil prices are predetermined with respect to current economic conditions. Based on those findings, we estimate the initial response of a macroeconomic variable, x_t, to an oil price shock with the following regression:

$$x_t = \alpha + \sum_{i=1}^{p} \theta_i x_{t-i} + \sum_{i=0}^{p} \beta_i \Delta oil_{t-i} + \sum_{i=0}^{p} \gamma_i NOPI_{t-i} + \varepsilon_t, \tag{2}$$

where Δoil_{t-i} is the percentage change in the price of oil in period $t-i$, $NOPI_{t-i}$ is the net oil price increase in period $t-i$ calculated using equation (1), α, θ_i, β_i, and γ_i are estimated parameters, and ε_t is the error term. Using the estimates of $\widehat{\beta}_0$ and $\widehat{\gamma}_0$, the contemporaneous response of x_t is calculated for both the NOPI and non-NOPI regimes, x_0^{NOPI} and $x_0^{non-NOPI}$,

$$x_0 = \widehat{\beta}_0 \Delta oil_0 + \widehat{\gamma}_0 NOPI_0, \tag{3}$$

where x_0 is the 0-period impulse response function of x_t to the oil price shock and Δoil_0 and $NOPI_0$ take the values given above.

The initial step in obtaining the s-period impulse response functions for x_s^{NOPI} and $x_s^{non-NOPI}$ is to estimate the following regression[5]:

[5] This model is more flexible than the NOPI model of Hamilton (1996, 2003, 2011), as it nests Hamilton's NOPI model ($\delta_i = 0\ \forall i$) and the linear model ($\phi_i = 0\ \forall i$) as special cases. It also does not exclude responses to oil price changes that occur in the non-NOPI regime. The cost of using our more general model is the loss of efficiency resulting from the inclusion of potentially irrelevant variables.

$$x_t = \alpha + \sum_{i=s}^{s+p-1} \rho_i x_{t-i} + \sum_{i=s}^{s+p-1} \delta_i \Delta oil_{t-i} + \sum_{i=s}^{s+p-1} \phi_i NOPI_{t-i} + \nu_t^s, \tag{4}$$

where α, ρ_i, δ_i, and ϕ_i are estimated parameters and ν_t^s is the error term. The impulse response functions at period s are calculated by multiplying the period s estimated coefficients by the time 0 response vectors, $[x_0^{NOPI}, \Delta oil_0^{NOPI}, NOPI_0^{NOPI}]'$ and $[x_0^{non-NOPI}, \Delta oil_0^{non-NOPI}, NOPI_0^{non-NOPI}]'$, for the NOPI and non-NOPI regimes, respectively,

$$x_s = \widehat{\rho}_s x_0 + \widehat{\delta}_s \Delta oil_0 + \widehat{\phi}_s NOPI_0. \tag{5}$$

Given that most macroeconomic data is nonstationary, we transform all of the data into their period-by-period percentage changes. We then calculate the cumulative impulse response functions, CR_s, to present all of the variables, except the inflation rate, in level form[6]:

$$CR_s = \sum_{j=0}^{s} x_j. \tag{6}$$

One key question in the oil price shock literature is whether oil price shocks have strictly linear effects on key economic variables or non-linear effects when the price of oil is in the NOPI regime. The linear model best represents the impact of oil price shocks on key economic variables when $\widehat{\gamma}_0 = 0$ in (2) and $\widehat{\phi}_s = 0$ in (4). In that case, the impulse response functions from an oil price increase in the NOPI regime, x_s^{NOPI}, are equal to the negative value of the impulse response functions from an oil price decrease in the non-NOPI regime, $-x_s^{non-NOPI}$. Alternatively, oil price shocks have nonlinear effects in the NOPI regime when the difference between cumulative impulse response functions, CD_s, for x_j^{NOPI} and $-x_j^{non-NOPI}$,

$$CD_s = \sum_{j=0}^{s} \left(x_j^{NOPI} - (-) x_j^{non-NOPI} \right), \tag{7}$$

[6]The cumulative impulse response functions convert the period-by-period percentage changes to the percentage deviations of that data from its long-run levels.

is significantly different from zero. For simplicity, we will refer to (7) as cumulative difference functions. To find the 95% confidence intervals for the cumulative difference functions, we follow Jorda (2005) and calculate the Newey-West covariance matrices for each estimated equation for x_s. The covariances across the equations for the different time horizons are calculated by estimating the full system of S equations by the seemingly unrelated regression model and then pulling out the relevant terms where S is the maximum number of periods for the impulse response functions. If the 95% confidence bands combined with the cumulative difference functions include zero in horizon s, then we cannot reject the null hypothesis that the impulse response functions of the nonlinear NOPI model and the linear non-NOPI model are equal at that horizon.[7]

2.2 Data

Table 1 displays the data and its mnemonics. Every data series is transformed into its quarterly percentage change. The crude oil price data was obtained from the Bureau of Labor Statistics. All of the other data were downloaded from the Federal Reserve Bank of St. Louis' FRED database. Impulse response functions were computed using data over the period of 1972Q1-2018Q1. That sample period was chosen to avoid the inflated effects of oil price shocks when using pre-early 1970s data as identified by Herrera et al. (2011).

2.3 Empirical Impulse Response Functions

Figures 1-4 present the cumulative impulse response functions and the cumulative difference functions for output, labor market variables, investment, and consumption and inflation following a 10% oil price shock.[8] In each figure, the cumulative impulse response functions,

[7] Alternatively, the 95% confidence bands for both of the impulse response functions can be computed, and if those bands do not overlap, the hypothesis of linearity is rejected. That test is not valid because it ignores the correlation between the responses in the two regimes. The bias in that test would be substantial because most of the coefficients used to compute the two impulse response functions are the same.

[8] The impulse responses for the inflation rate are the standard impulse response functions and not the cumulative impulse response functions.

(6), in the NOPI and non-NOPI regimes are displayed in the left-hand column and their respective cumulative difference functions, (7), along with their 95% confidence bands are shown in the right-hand column. In the left-hand column, the solid lines represent the cumulative impulse responses following a 10% oil price increase in the NOPI regime, while the dashed lines display the negative values from the cumulative responses following a 10% oil price decrease in the non-NOPI model. In the right-hand column, the solid line represents the cumulative difference functions and the dashed lines show their 95% percent confidence intervals.

2.3.1 Response of Output

Figure 1 shows that GDP, industrial production, and durable goods manufacturing decline significantly more after an oil price increase in the NOPI regime than in the non-NOPI regime. A 10% oil price increase in the NOPI regime is followed by a cumulative reduction in real GDP of about 1.5 percentage points over the next year. The estimated decline is roughly in line with the findings in Hamilton (2008). In our sample period, real GDP grew on average 2.7% a year, so a 10% oil price increase probably will not cause a recession, but it will produce a noticeable slowdown in output growth. In contrast, a 10% decrease in the oil price has minimal effects on real GDP. As for industrial production, it is a measure of output in manufacturing, mining, and electric and gas utilities.[9] There is no reason *a priori* to expect industrial production to respond any differently than real GDP to an oil price shock. In the NOPI regime, a 10% oil price increase pushes down industrial production by over 2.5 percentage points after a year. A 10% decrease in oil prices, however, only generates a slight increase in industrial production in the non-NOPI regime.

A substantial rise in oil prices is expected to negatively impact manufacturing more than the economy as a whole. Those high oil prices also could spur a large increase in energy production, which would have a positive effect on industrial production and GDP. For those

[9] https://bea.gov/faq/index.cfm?faq_id=73

reasons, we examine the impact of an oil price shock on the manufacturing of durable goods. Durable goods manufacturing represented 38% of all industrial production in 2012 and includes the following categories of production: wood product; nonmetallic mineral product; primary metal; fabricated metal product; machinery; computer and electronic product; electrical equipment, appliance, and component; motor vehicles and parts; aerospace and miscellaneous transportation equipment; furniture and related product; and miscellaneous.[10] Five categories, all of which are highly energy-dependent, accounted for most of the durable goods manufacturing: fabricated metal product; machinery; computer and electronic product; motor vehicles and parts; and aerospace and miscellaneous transportation equipment. In the NOPI regime, durable goods manufacturing falls by more than 3 percentage points in the year after the 10% oil price increase and continues to decline further in the second year. The impulse response functions reveal durable goods manufacturing rises by a modest 0.8 percentage point after a 10% decline in oil prices in the non-NOPI regime.

2.3.2 Labor Market Variables

Blanchard and Gali (2009) find oil price shocks have a smaller effect on output when wages are flexible than when wages are sticky or rigid. Specifically, an economy with flexible wages produces a larger drop in the real wage rate after an oil price increase, which then puts more downward pressure on the real marginal cost. That downward pressure mitigates some of the rise in the marginal cost caused by the higher oil prices, and as a result, limits the decline in output. Figure 2 shows the impact of an oil price shock on the hourly nominal wage and on the weekly hours worked for nonfarm employees. Consistent with Blanchard and Gali's (2009) theoretical model, an oil price increase generates a significantly higher nominal wage in the NOPI regime than in the non-NOPI regime. Non-farm weekly hours worked, on the other hand, fall by about 0.5 percentage points in the first year after a 10% oil price increase in the NOPI regime, which is significantly higher than its response in the non-NOPI

[10] Source: Federal Reserve Board data release notes.

regime. Any plausible macroeconomic model of the transmission of oil price shocks to the economy needs to replicate those particular labor market responses. The model presented in the next section, like Blanchard and Gali (2009), assigns a key role to labor market rigidities. An important distinction of our model is we focus on downward rigid nominal wages as an explanation for the asymmetric responses generated in the NOPI model. Blanchard and Gali (2009), in contrast, assume real wages are sticky, which results in symmetric responses to oil price shocks.

2.3.3 Investment

Figure 3 presents the impact of an oil price shock on private fixed investment, residential investment, nonresidential investment, and investment in mining structures. A 10% oil price increase in the NOPI regime produces a significantly larger decline in private fixed investment, residential investment, and nonresidential investment than in the non-NOPI regime. Private fixed investment falls more than 3 percentage points in the year after a 10% oil price increase in the NOPI regime, while a similar oil price decline in the non-NOPI regime has little effect on private fixed investment. The negative response of private fixed investment to oil price increases, however, is dampened by the fact that higher oil prices usually stimulate energy-related investment. As a result, we also examine the responses of residential investment, nonresidential investment, and investment in mining structures to oil price shocks.

Residential investment declines much more than aggregate investment after an oil price increase in the NOPI regime. A 10% oil price increase in the NOPI regime causes a nearly 8 percentage point decline in residential investment over the next year, while a same-sized decline in the non-NOPI regime increases residential investment by a mere 1 percentage point over the next year. Nonresidential investment declines by about 2 percentage points in the year after a 10% oil price increase in the NOPI regime with much of the drop due to a large fall in equipment investment. In the non-NOPI regime, an oil price shock has little effect on nonresidential investment. An oil price increase, however, pushes up investment in mining structures by roughly the same amount in both the NOPI and non-NOPI regimes. Those results indicate firms adjust their levels of mining investment more based on the size of the oil price shock than whether oil prices are in the NOPI regime.

2.3.4 Consumption and Inflation

Figure 4 displays the cumulative impulse response functions for the NOPI and non-NOPI regimes and the cumulative difference functions for real personal consumption expenditures (PCE), real core PCE, and the core PCE inflation rate. The statistically significant asymmetry effects of an oil price shock between NOPI and non-NOPI regimes observed in much of the national income data also hold for real PCE and real core PCE. Specifically, a 10% oil price increase in the NOPI regime causes real PCE and real core PCE to decline by 1% and 1.3%, respectively, in the first year. As expected, real core PCE declines more than real PCE due to a shift in spending from non-energy consumption to energy consumption. A 10% decrease in oil prices, on the other hand, has minimal effects on real PCE and real core PCE over the same time horizon. As for inflation, the core PCE inflation rate is 0.4% above its pre-shock level one year after a 10% oil price increase in the NOPI regime. That number continues to fall until the core PCE inflation rate essentially returns to its pre-shock level within two years. In the non-NOPI regime, a 10% oil price decrease produces a very modest decline in the core PCE inflation rate. The difference between the responses of the core PCE inflation rate in the NOPI and non-NOPI regimes, however, is not statistically significant.

3 Theoretical Model

This section develops a dynamic stochastic general equilibrium (DSGE) model with price stickiness and downward rigid nominal wages to examine the asymmetric effects of key economic variables to an energy price shock. Price setting follows a Calvo (1983) model of random adjustment, while nominal wages are perfectly flexible on the upside but rigid on the downside. Energy is demanded by households as a consumption good and by firms as a factor of production. The energy endowment each period is sufficient to meet market demand at its exogenously-determined price.

3.1 Households

Households are infinitely-lived agents who prefer consumption, c_t, but dislike labor, n_t. Each period, households maximize their utility,

$$U = E_t \sum_{j=0}^{\infty} \beta^j \left[\ln \left(c_{t+j} - \phi_c h_{t+j} \right) - \phi_n \frac{n_{t+j}^{1+\zeta} - 1}{1+\zeta} \right] \tag{8}$$

subject to a consumption aggregator, budget constraint, capital accumulation equation, and a nominal wage rigidity that restricts the nominal wage from falling. E_t is the expectational operator at time t, $0 \leq \beta < 1$ is the discount factor, $0 \leq \phi_c < 1$ is the external habit persistence parameter, h_t is the habit persistence variable that is equal to lagged aggregate consumption ($h_t = c_{t-1}$), ζ is the labor supply elasticity, and $\phi_n > 0$. Aggregate consumption is a CES composite of energy consumption, $e_{h,t}$, and non-energy consumption, $c_{n,t}$,

$$c_t = \left(a_1 e_{h,t}^{\upsilon_h} + a_2 c_{n,t}^{\upsilon_h} \right)^{1/\upsilon_h}, \tag{9}$$

where $1/(1-\upsilon_h)$ is the elasticity of substitution between non-energy and energy consumption, and $a_1 > 0$ and $a_2 > 0$ are calibrated such that $a_1(e_{h,t}/c_t)^{\upsilon_h}$ and $a_2(c_{n,t}/c_t)^{\upsilon_h}$ are set equal to energy's and non-energy's shares of consumption, respectively.

The households' budget constraint shows the real value of inflows and outflows of funds:

$$\left(\frac{P_{n,t}}{P_t} \right) (c_{n,t} + i_t) + \left(\frac{P_{e,t}}{P_t} \right) e_{h,t} + b_t = \frac{R_{t-1} b_{t-1}}{\pi_t} + d_t + w_t n_t + \left(\frac{P_{n,t}}{P_t} \right) q_t k_t. \tag{10}$$

At the beginning of each period, households receive real income from last period's bond holdings, $R_{t-1}b_{t-1}/\pi_t$, where R_t is the gross nominal interest rate between periods t and $t+1$, π_t is the gross headline inflation rate between periods $t-1$ and t, and b_t is the real value of bond holdings. Households then receive their labor income, $w_t n_t$, capital income, $(P_{n,t}/P_t)q_t k_t$, and their share of profits from firms and the energy sector, d_t, where w_t is the real wage rate, $P_{n,t}$ is the aggregate price level for non-energy output (i.e., core price level), P_t is the aggregate price level (i.e., headline price level), and q_t is the real rental rate of capital. Households use those funds to purchase non-energy consumption goods, $(P_{n,t}/P_t)c_{n,t}$, investment goods, $(P_{n,t}/P_t)i_t$, energy, $(P_{e,t}/P_t)e_{h,t}$, and bond holdings, b_t, where i_t is real investment, and $P_{e,t}$ is the price of energy.

Households invest in capital and rent it to the firms in a perfectly competitive market. Once investment decisions are made, capital evolves as follows:

$$k_{t+1} - k_t = i_t \left(1 - S\left(\frac{i_t}{i_{t-1}}\right)\right) - \delta k_t, \tag{11}$$

where $S(\cdot)$ is an investment adjustment cost function that represents the resources lost in the conversion of investment to capital. Following Christiano, Eichenbaum, and Evans (2005), we assume that $S(1) = S'(1) = 0$ and $\kappa = S''(1) > 0$. Households supply labor in a perfectly competitive market, but they will not accept a nominal wage lower than the level of the previous period. That restriction results in the following inequality constraint:

$$P_{t+1}w_{t+1} \geq \gamma P_t w_t, \tag{12}$$

where $\gamma \geq 0$ measures the degree of downward nominal wage rigidity. Nominal wages are absolutely downward rigid when $\gamma \geq 1$, but they are perfectly flexible when $\gamma = 0$. Our paper assumes nominal wages are downward rigid, $\gamma \geq 1$, based in part on empirical evidence from the U.S. (e.g., see Gottschalk 2005, Barattieri, Basu, and Gottschalk 2014, and Hazell and Taska 2018). During the periods when (12) binds, households supply more labor than demanded, so the households' first-order condition for labor does not bind.

3.2 Firms

Firms are monopolistically competitive producers of non-energy output, $y_{n,t}$. Firm f uses its inputs of capital, $k_{f,t}$, labor, $n_{f,t}$, and energy, $e_{f,t}$, to produce its output, $y_{f,t}$, according to the following production function:

$$y_{f,t} = \left(bk_{f,t}^{\upsilon_f} + (1-b)e_{f,t}^{\upsilon_f}\right)^{\alpha/\upsilon_f} (n_{f,t})^{1-\alpha}, \tag{13}$$

where $1/(1-\upsilon_f)$ is the elasticity of substitution between energy and capital, $0 < b < 1$, and $0 < \alpha < 1$. The capital and labor used by firm f are rented for the nominal capital rental rate of $P_{n,t}q_t$ and the nominal wage rate of $P_t w_t$, respectively. Firm f also purchases its energy input in a perfectly competitive market for a price of $P_{e,t}$. Given those capital, labor, and energy costs, firm f minimizes its production costs:

$$P_{n,t}q_t k_{f,t} + P_t w_t n_{f,t} + P_{e,t}e_{f,t} \tag{14}$$

subject to (13).

The differentiated output, $y_{f,t}$, produced by a continuum of many firms ($f \in [0,1]$) are combined to generate aggregate non-energy output, y_t, using the Dixit and Stiglitz (1977) method:

$$y_t = \left[\int_0^1 y_{f,t}^{(\epsilon-1)/\epsilon} df\right]^{\epsilon/(\epsilon-1)}, \tag{15}$$

where $-\epsilon$ is the price elasticity of demand for $y_{f,t}$. Since firm f sells $y_{f,t}$ at a price of $P_{f,t}$, cost minimization on the part of households implies the demand for $y_{f,t}$ is a decreasing function of its relative price:

$$y_{f,t} = \left(\frac{P_{f,t}}{P_{n,t}}\right)^{-\epsilon} y_t, \tag{16}$$

where $P_{n,t}$ is a nonlinear price index of a continuum of non-energy output:

$$P_{n,t} = \left[\int_0^1 P_{f,t}^{(1-\epsilon)} df \right]^{1/(1-\epsilon)}. \tag{17}$$

Households purchase non-energy output as either non-energy consumption or investment:

$$y_t = c_{n,t} + i_t. \tag{18}$$

Price-setting behavior follows the Calvo (1983) model of random adjustment. Each period, a fraction of firms, $(1-\eta)$, have the opportunity to readjust their prices optimally, while the remaining fraction, η, raise their prices by last period's core inflation rate, $\pi_{n,t-1}$. When presented with an optimal price adjustment opportunity, firm f selects a price, $P_{f,t}^*$, that maximizes the present real value of current and expected future profits given the probability of future adjustment opportunities:

$$\max_{P_{f,t}^*} E_t \left[\sum_{j=0}^{\infty} \beta^j \eta^j \lambda_{t+j} \left(\frac{\Pi_{n,t+j} P_{f,t}^*}{P_{t+j}} y_{f,t+j} - w_{t+j} n_{f,t+j} - \frac{P_{n,t+j}}{P_{t+j}} q_{t+j} k_{f,t+j} - \frac{P_{e,t+j}}{P_{t+j}} e_{y,t+j} \right) \right], \tag{19}$$

where

$$\Pi_{n,t+j} = \left\{ \begin{array}{ll} \pi_{n,t} \times \pi_{n,t+1} \times \ldots \times \pi_{n,t+j-1} & \text{for } j \geq 1 \\ 1 & \text{for } j = 0 \end{array} \right\} \tag{20}$$

subject to the demand for its product, (16), and the input factor demands from its cost minimization problem, (14).

The headline price level, P_t, is a weighted function of the core price level, $P_{n,t}$, and the price of energy, $P_{e,t}$:

$$P_{n,t}^{(1-\varpi)} P_{e,t}^{\varpi} = P_t, \tag{21}$$

where ϖ is energy's share of output in the steady state and $(1-\varpi)$ is non-energy's share of output.[11] Thus, the impact of core and energy prices on the headline price level depends on

[11] Energy's, ϖ, and non-energy's, $(1-\varpi)$, shares of output are equal to $P_e e/(P_n c_n + P_e e)$ and $P_n c_n/(P_n c_n +$

the size of their respective shares of output.

3.3 Energy

Energy is used by households as a consumption good and by firms as a factor input. Therefore, aggregate energy, e_t, comprises energy consumed by both households and firms:

$$e_t = e_{h,t} + e_{f,t}. \tag{22}$$

The energy endowment is sufficient to meet market demand at an exogenously determined price. Following Wei (2003), the real price of energy, $p_{e,t} = P_{e,t}/P_t$, is modeled as an AR(1) process:

$$\ln(p_{e,t}) = \rho_e \ln(p_{e,t-1}) + \varepsilon_t, \tag{23}$$

where $0 \leq \rho_e < 1$ and $\varepsilon_t \sim N(0, \sigma_e)$.[12]

3.4 Monetary Policy

Monetary policy is conducted via a Taylor (1993) style nominal interest rate rule with interest rate smoothing. That is, the central bank adjusts its nominal interest rate target, R_t, in response to changes in the lagged nominal interest rate, R_{t-1}, the core inflation rate, $\pi_{n,t}$, and non-energy output, y_t:

$$\ln(R_t/R) = \theta_R \ln(R_{t-1}/R) + (1-\theta_R)[\theta_\pi \ln(\pi_{n,t}/\pi_n^*) + \theta_y \ln(y_t/y_t^P)], \tag{24}$$

where π_n^* is the gross steady-state core inflation rate, y_t^P is potential non-energy output, $0 \leq \theta_R < 1$, $\theta_\pi > 1$, and $\theta_y \geq 0$. Potential non-energy output is the level of non-energy output that would exist in the absence of nominal price and wage frictions.

$P_e e$), respectively, where P_e, P_n, e, and c_n are the steady-state values of $P_{e,t}$, $P_{n,t}$, e_t, and $c_{n,t}$.

[12] Our qualitative results are the same if the energy price is assumed to follow an ARMA(1,1) process or if the model is solved with the quantity of energy rather than the energy price being exogenous.

4 Equilibrium and Calibration

Our model's systematic equilibrium comprises the set of difference equations representing the model's first-order conditions, identity equations, and exogenous energy price shock process. The existence of a long-run trend in the core price level, the headline price level, and the price of energy means that all of the nominal variables, except R_t, must be divided by P_t to induce stationarity in the model.[13] Our system of equations then is linearized around its nonstochastic steady state and the standard solution techniques (e.g., see Sims 2002) are utilized to find the rational expectations solution. Finally, the Holden and Paetz (2012) algorithm is used to simulate our linear DSGE model with a downward rigid nominal wage inequality constraint.[14]

Table 2 displays the parameters calibrated to quarterly values commonly used in the literature. Beginning with households, the discount factor, β, is parameterized to 0.99, the degree of habit persistence, ϕ_c, is set to 0.7, the degree of downward nominal wage rigidity, γ, equals 1, and the preference parameter, ϕ_n, is calibrated so the steady-state level of labor, n^*, equals 0.3. The Frisch labor supply elasticity, $1/\zeta$, is fixed to Heathcote, Storesletten, and Violante's (2014) estimate of 0.72.[15] Our calibrated values of a_1 and a_2 from the aggregate consumption equation, (9), are set so the ratio of energy used in consumption to aggregate consumption equals its average of 0.043 from 1972:Q1 to 2017:Q4.[16] The parameter υ_h used to calculate the elasticity of substitution between energy and non-energy consumption, $1/(1-\upsilon_h)$, equals -0.9. That value used by Gavin, Keen, and Kydland (2015) implies the two goods are compliments. We assume the price elasticity of demand, ϵ, is 6, so the

[13] We assume the core price level, the headline price level, and the price of energy all have identical long-run trends, so energy's share of the economy remains constant in the long run.

[14] Holden and Paetz (2012) develops a method to solve and simulate DSGE models with occasionally binding constraints. In addition to solving the model when the constraint binds, their algorithm uses a hybrid local/global approximation to account for the possibility the constraint will bind in the future, even when the constraint is not currently binding.

[15] Heathcote et al. (2014) estimates the Frisch elasticity to be 0.72 when a household is defined as a husband and a wife. Given that many DSGE models utilize higher values for the Frisch labor supply elasticity, we examine the sensitivity of our results to those higher values later in the paper.

[16] The ratio of energy consumption to aggregate consumption is calculated as the average ratio of Nondurable Goods: Gasoline and Other Energy Goods to Personal Consumption Expenditures.

steady-state markup of price over marginal cost is 20%. The quarterly capital depreciation rate, δ, is calibrated to 0.025, while the investment adjustment costs parameter, κ, is set to Christiano et al.'s (2005) estimate of 2.5.

In the production function, capital and energy's share in production, α, is set to 0.33, while a is fixed to 0.038, which is equal to energy's average share in the production of output from 1972:Q1 to 2017:Q4.[17] We follow Gavin et al. (2015) and parameterize υ_f to -0.9. Since $\upsilon_f < 0$, capital and energy are complimentary goods. The Calvo (1983) probability of non-optimal price adjustment, η, is calibrated to 0.75, which implies a firm, on average, optimally readjusts its price once a year. The steady-state relative prices of energy and non-energy, P_e and P_n, are assumed to be equal. As for the policy rule, the parameters on inflation and output, θ_π and θ_y, are calibrated to Taylor's (1993) estimates of 1.5 and 0.125, respectively, while the coefficient on the lagged interest rate, θ_R, is fixed to 0.7.[18] The gross steady-state quarterly core inflation rate, π_n^*, is equal to 1.005, which is consistent with a 2% annual inflation rate target. Finally, the AR coefficient, ρ_e, in the energy price shock process is set to 0.95 as in Wei (2003).

5 Model Results

5.1 Impulse Response Functions

Figure 5 shows the impulse response functions of key economic variables to an 80% increase in the energy price both with flexible nominal wages and downward rigid nominal wages ($\gamma = 0$ and $\gamma = 1$, respectively). Wei (2003) notes that an 80% energy price increase matches the rise

[17] The 2017 Annual Energy Review publishes annual data on energy expenditures as a share of GDP (see Table 1.7) through 2015. We use that data to calculate energy's share of GDP from 1972 to 2015. Next, energy's share of GDP is extrapolated for 2016 and 2017 by assuming its growth rate is identical to the growth rate of personal consumption expenditures' measure of energy goods and services in the National Income and Product Accounts. We then calculate energy's share of production by subtracting the consumption of energy goods and services as a share of GDP from total energy expenditures as a share of GDP.

[18] Since we are using a quarterly model, the standard Taylor (1993) rule coefficient on output, θ_y, of 0.5 is divided by 4.

in U.S. energy prices during the 1973-1974 energy crisis. The impulse response functions for output, investment, aggregate consumption, non-energy consumption, core inflation rate, and labor are the percent deviations from the steady state, while the responses for the nominal wage and nominal wage growth rate are the percentage change from its initial value and the actual rate of growth, respectively. In a linearized DSGE model, identically-sized increases and decreases in energy prices have symmetric effects. The presence of the downward rigid nominal wages, however, causes a rise in energy prices to generate differently-sized effects than a same-sized decline in energy prices. The difference between the impulse responses in Figure 5 illustrates the approximate asymmetric effects of an energy price shock in our model with downward rigid nominal wages.

The dashed line in Figure 5 reveals the impact of a rise in energy prices in a model with flexible nominal wages. In that model, an energy price increase immediately pushes up production costs, which causes firms to reduce their supplies of output and raise prices. The lower supply of output puts downward pressure on real wages and capital rentals by reducing firms' demand for labor and capital. Households respond to higher energy prices and smaller capital rents by reducing their demand for energy consumption and investment. Higher energy prices also reduce the relative price of non-energy goods, so households substitute some of their lost energy consumption for additional non-energy consumption to accommodate their preferences for habit persistence in aggregate consumption. That shift moderates the declines in aggregate consumption and non-energy output after an energy price increase. In the labor market, firms demand less labor, but households respond to the decline in aggregate consumption by increasing their supplies of labor and decreasing their leisure.[19] The increase in labor supply combined with the decrease in labor demand pushes down the real wage but pushes up labor hours. The initial jump in headline inflation, however, is large enough to dominate the fall in the real wage, so the nominal wage rises.

[19] Bodenstein, Guerrieri, and Gust (2013) argues households do not increase labor supply after a negative energy shock when a Greenwood, Hercowitz, and Huffman (1988) style of utility function is used instead of the additively separable utility function employed here. One impact from labor supply not rising is that non-energy consumption decreases rather than increases after a positive energy price shock.

In subsequent periods, elevated energy prices retreat slowly, which leads to a moderation of inflation. As more firms have an opportunity to raise their prices in response to the energy price increase, the supply of output proceeds to fall for several more periods. Furthermore, the slow adjustment of consumption and investment due to habit persistence in consumption and investment adjustment costs means households' demand in the non-energy goods market continues to decline in the short term. The continued decline in output demand and supply causes output to fall for another four periods. Reduced output production lowers labor demand, which puts downward pressure on the real wage and labor hours. The decline in the real wage dominates the moderation of inflation, so the nominal wage growth rate turns negative. After several periods, more firms start to lower their prices in response to the declining energy prices, which stimulates output and pushes the key economic variables back toward their respective steady states.

The solid line in Figure 5 shows the effects of downward rigid nominal wages on the responses of key economic variables to an energy price increase. The main effects of the downward wage constraint begin to occur in the first period after the energy price increases when the downward nominal wage rigidity prevents the nominal wage growth rate from declining. Firms react to those higher labor costs by reducing their output further and by raising their prices higher. The price increases cause households to enhance their cuts to aggregate consumption and investment. The effects of the downward nominal wage rigidity continue directly to impact the economy as long as the nominal wage is higher than it otherwise would be in the absence of the downward rigidity. Even after the downward wage constraint is no longer binding, previous pricing decisions and lower capital investment continue to dampen output for a few more periods relative to the flexible nominal wage specification. The nominal wage growth rate in our model remains at zero for several periods, which indicates the downward nominal wage rigidity remains binding during those periods. As a result, the downward nominal wage rigidity leads to a larger and more persistent decline in output than in the flexible nominal wage model.

Figure 6 displays the impulse response functions of key economic variables to an 80% decrease in the energy price. The solid line represents responses of the model with downward rigid nominal wages and the dashed line denotes responses of the model with flexible nominal wages. The key finding from those impulse responses is that a large fall in energy prices only causes the downward rigid nominal wage constraint to bind in the initial period. The nominal wage constraint binds because lower energy prices push down the price level at a faster rate than firms' increased demand for labor drives up the market clearing real wage. Hence, the actual real wage is above its market clearing level, which causes price-adjusting firms to limit the decline in their prices leading to a slightly smaller increase in output. Even though the downward rigid wage constraint does not bind in future periods, the output response is slightly lower for a few more periods than in the flexible wage model because price stickiness delays the opportunity for initial price-adjusting firms to adjust their prices again.

Our findings indicate a large energy price decrease generates impulse response functions for the downward rigid nominal wages model that are very similar to the responses for the flexible nominal wage model, especially in periods $t+1$ and beyond. Since energy price increases and decreases have symmetric effects on the flexible wage model, the downward rigid wage model's asymmetric impulse responses are primarily due to the wage constraint binding after an energy price increase as opposed to after an energy price decrease. Thus, the remainder of our analysis focuses on comparing the impact of energy price increases on our downward rigid nominal wages model and on our flexible nominal wage model.

5.2 Decision Rules

Figure 7 presents the period $t+1$ decision rules for key economic variables as a function of an energy price shock, ε_t, that ranges from a $0\% - 100\%$ increase in the price of energy. We focus on the period $t+1$ decision rules because if ε_t is large enough, the downward rigid nominal wage constraint begins to bind in the first period after an energy price increase (i.e., period $t+1$). The dashed line displays an energy price increase's impact on a model with flexible nominal wages, while the solid line shows its effect on a model with downward rigid nominal wages. Decision rules for the model with flexible wages are linear because the model is solved using standard linearization techniques. The downward rigid nominal wage constraint, however, introduces a nonlinear feature into the otherwise linear flexible wage model. Thus, any deviation of the downward rigid wage model's decision rules from the flexible wage model's decision rules represents the asymmetric and nonlinear effects, which are attributable to the downward rigid nominal wage constraint.

The results in Figure 7 reveal that for small energy price shocks, $\varepsilon_t \leq 15\%$, the nominal wage growth rate is positive, so both models generate identical results because the downward rigid nominal wage constraint does not bind. When $\varepsilon_t > 15\%$, the nominal wage cannot fall in the downward rigid nominal wages model so output, aggregate consumption, non-energy consumption, and investment decline at faster rates than in the flexible wage model, while the core inflation rate rises at a quicker rate. The spread between the solid and dashed lines continues to grow as the size of the oil price increase rises, which indicates the responses from the model with downward rigid nominal wages are rising in a nonlinear manner. That result suggests a model with downward rigid nominal wages generates responses to the energy price increase consistent with both Hamilton's (1996, 2003, 2011) net oil price increase model and Kilian and Vigfusson's (2013) net oil price change model.

5.3 Sensitivity Analysis

The asymmetric effects of an energy price shock in a New Keynesian model with downward rigid nominal wages depends, sometimes critically, on the calibration of certain parameters. Specifically, output's response to an energy price shock depends on the value of the labor supply elasticity, the degree of price stickiness, the amount of steady-state inflation, and the degree of downward rigid nominal wages. Figure 8 illustrates the impact of those features on output's response to an 80% increase in the energy price.

The top, left-hand graph of Figure 8 illustrates the impact of the labor supply elasticity on output's response to an 80% energy price increase. Most models with downward rigid nominal wages assume the labor supply elasticity is very low. For example, Benigno and Ricci (2011) set the labor supply elasticity to 0.4, while Schmitt-Grohe and Uribe (2016) set that parameter equal to 0. Our baseline model calibrates the labor supply elasticity to Heathcote et al.'s (2014) estimate of 0.72. Since other papers, such as Christiano and Eichenbaum (1992), use a much higher labor supply elasticity, we also examine output's response when the labor elasticity is equal to 2. The solid and dashed lines display the impulse responses for a downward rigid nominal wages model and a flexible nominal wages model, respectively, when the labor supply elasticity (LSE) equals 0.72. A comparison of those impulse responses reveals output falls substantially more when nominal wages are downward rigid. When the labor supply elasticity is set to 2, the dash-dotted line and the dotted line show output's responses are almost identical in the models with downward rigid nominal wages and flexible nominal wages. That is, the asymmetric response of output to an energy price shock in a model with downward rigid nominal wages essentially disappears when the labor supply elasticity is 2. The intuition being that a higher labor supply elasticity indicates a flatter labor supply curve. When an energy price increase causes labor demand to decrease, a flatter labor supply curve limits the size of the decline in the real wage. A large drop in the real wage is necessary to offset the inflationary effects of the energy price increase so that the downward rigid nominal wage constraint binds. A binding downward wage constraint is essential for the model to generate asymmetric responses after an energy price increase.

The effect of the degree of price stickiness on output's response to an energy price increase is displayed in the top, right-hand graph of Figure 8. The solid and dashed lines show the impact of an 80% energy price increase on output in the downward rigid nominal wages and flexible nominal wages models, respectively, when prices change on average once a year, $\eta = 0.75$. We then examine the effect of an energy price increase when prices adjust on average once every 2.5 quarters, $\eta = 0.6$. The dash-dotted and dotted lines illustrate the responses of output in the downward rigid wage and flexible nominal wage models, respectively, when

$\eta = 0.6$. Our results show a modest reduction in the degree of price stickiness leads to slightly larger responses in the short run, but those responses are not as persistent. In terms of the degree of asymmetry, a higher degree of price stickiness causes the asymmetry in the model to persist for a longer period.

The bottom, left-hand graph of Figure 8 illustrates how the steady-state inflation rate impacts output's response to an energy price shock. The dashed line displays output's response for a flexible nominal wage model. Regardless of the level of the steady-state inflation rate, the impulse response functions for output are always the same in the flexible wage model. The solid, dotted, and dash-dotted lines represent output's response to an energy price increase in the downward rigid nominal wages model when the steady-state annual inflation rate is 0%, 2%, and 4%, respectively. The differences between each line and the dashed line indicates the degree of asymmetry in output's response to an energy price increase. Those results demonstrate asymmetry is the greatest when the steady-state inflation rate is low, 0%, and is much more muted when the steady-state inflation rate is high, 4%. It follows that when the steady-state inflation rate is higher, the real wage has to fall more before it hits the downward nominal wage rigidity that causes the asymmetric responses after an energy price increase.

The degree of the downward nominal wage rigidity also influences output's response to an energy price increase. The bottom, right-hand graph of Figure 8 shows output's response becomes more asymmetric as the degree of downward nominal wage rigidity rises. The dashed line displays output's response to an energy price shock when nominal wages do not have a downward constraint ($\gamma = 0$). The solid, dotted, and dash-dotted lines represent output's response to an energy price increase when nominal wages must rise by at least 0.5% a period ($\gamma = 1.005$), cannot fall at all ($\gamma = 1.000$), and can only fall by 1% a period ($\gamma = 0.990$), respectively. The differences between each line and the dashed line represent the impact of downward nominal wage rigidity on the asymmetry in output's response to an energy price increase. When nominal wages exhibit a high degree of downward rigidity (γ is large), an energy price increase is more likely to push down the real wage enough to cause the nominal wage to hit its downward constraint. The sooner the nominal wage bumps into that constraint the greater the asymmetry in the impulse response functions after an energy price increase.

Our sensitivity analysis results reveal that the ability of an energy price increase to generate asymmetric impulse response functions in a model with downward rigid nominal wages depends critically on a few key parameter values. Specifically, we show an energy price shock is more likely to produce asymmetric responses when the labor supply elasticity is low, the degree of price stickiness is large, the steady-state inflation rate is low, and the degree of downward rigid nominal wages is high.

5.4 Demand or Supply Shock: Does It Matter?

Our model assumes an energy price shock is exogenous to the economy and the energy endowment is sufficient to meet energy demand at the exogenously-determined price. Since the energy price does not respond to changes in the domestic economy, our model views the energy price shock as a disturbance that originates internationally. A sampling of the largest energy price shocks over our estimation period is consistent with that assumption. For example, the large oil price increases in 1973-1974, 1979-1980, and 1990-1991 are usually attributed to oil supply disruptions, while the 2002-2008 oil price spike is often attributed to the increase in worldwide demand particularly from China and India.

One drawback to our model is that it does not distinguish between energy price shocks caused by foreign changes in energy demand and foreign changes in energy supply. We can use an open economy DSGE model by Balke and Brown (2018), however, to infer how energy price shocks caused by changes in foreign energy demand and supply impact our model. Specifically, Balke and Brown separately examine the impact of a rise in energy prices caused by an increase in foreign demand or by a decrease in foreign supply. The authors find an increase in foreign energy demand generates a larger rise in domestic prices and a smaller decline in domestic output than a comparable decline in foreign energy supply. The rationale for their result is straightforward. An increase in foreign energy demand usually is caused by a growing foreign economy that is demanding and producing more goods and services. Some of the increased foreign demand for goods and services is produced in the domestic country. Therefore, a rise in energy prices precipitated by a growing foreign economy demanding more energy pushes up the domestic country's exports. Those higher exports dampen the decline in domestic output caused by higher energy prices and put more upward pressure on domestic prices. In contrast, a reduction in foreign energy supply pushes down output worldwide, which leads to a decline in international trade. If the decreases in domestic exports and domestic imports offset each other, then an energy price increase caused by a reduction in foreign energy supply has no additional effects on our model.

The findings in Balke and Brown (2018) suggest our model is best at explaining the effects of an energy price increase caused by a decline in the foreign supply of energy. Balke and Brown's results, however, have implications for how our model's results would change when an energy price increase is caused by increased foreign demand for energy. Specifically, an increase in foreign demand would lead to a smaller decline in domestic output and a larger rise in the price level than a decrease in foreign supply. Those changes have implications for when the economy hits the downward rigid nominal wage constraint. The smaller decline in output means the real wage will not decrease as much in the initial periods, while the larger rise in the price level implies the inflation rate will be higher initially. The combination of a higher initial inflation rate and a smaller decline in the real wage signifies the economy is less likely to hit the downward rigid nominal wage constraint. As a result, an energy price shock caused by a foreign supply disruption will have a larger asymmetric effect on the economy than an energy shock caused by an increase in foreign demand.

6 Conclusion

This paper introduces downward rigid nominal wages into a standard New Keynesian model in which energy is both a factor of production and a consumption good. An energy price increase that causes the downward nominal wage constraint to bind limits the wage rate's decline, which forces firms to reduce output more than they would otherwise without the constraint. Since that mechanism is unimportant when energy prices fall, the downward nominal wage constraint causes output to react asymmetrically to oil price shocks. That constraint, however, has no real impact on the nominal wage after an energy price decrease, so output does not rise as aggressively. Therefore, downward rigid nominal wages cause energy price shocks to have asymmetric effects on the macroeconomy. Our results indicate the degree of those asymmetric effects depends on the labor supply elasticity, the amount of price stickiness, the steady-state inflation rate, and the degree of downward nominal wage rigidity.

The model with downward rigid nominal wages provides a theoretical explanation for the economy's response to oil price shocks as originally proposed by Hamilton (1996, 2003). Specifically, Hamilton's "net oil price increase" model finds output experiences a larger decline when the price of oil reaches a new near-term high. We contend that large oil price shocks, which push the price of oil to new highs relative to recent experience, are much more likely to cause the downward nominal wage constraint to bind. For example, the 64% increase in the price of oil from February 1980 to February 1981 was so large that most energy-intensive firms were unable to lower wages enough to offset the jumps in their marginal costs and as result, were forced to further reduce their output. The example illustrates that a downward rigid nominal wage constraint is an appropriate mechanism to include in any theoretical model seeking to replicate the stylized facts of Hamilton's "net oil price increase" model.

One potential concern with our specification of downward nominal wage rigidity is that the constraint is absolute. Nominal wages are perfectly flexible, but they cannot decline past a certain level. In the real world, nominal wages likely face asymmetric adjustment costs that increase in size as nominal wages fall further below a certain threshold. Such a modification to our New Keynesian model would change our quantitative results, but it would not change our qualitative results. A more accurate specification of the downward nominal wage constraint is relevant to questions, such as determining the optimal policy response to oil price shocks, where the precise quantitative results matter. Those topics, however, are beyond the scope of this paper and are left for future research.

A Appendix

The empirical impulse response functions presented in Section 2.3 examine the impact of a 10% energy price increase in both the NOPI and non-NOPI regimes, while the model impulse response functions reported in Section 5.1 analyze the effects of an 80% energy price increase. The model impulse responses establish that our theoretical explanation is consistent with the empirically-observed effects of an energy price increase. This analysis presumes that an energy price shock that forces the downward rigid nominal wage constraint to bind in our theoretical model is a proxy for an energy price shock in the NOPI regime of our empirical model. Those two shocks, however, are not directly comparable because our theoretical model's downward rigid nominal wage constraint only binds when the energy price is 15% or more above its steady state, whereas the empirical model enters the NOPI regime whenever the nominal energy price reaches a three-year high.

This appendix presents an alternative set of model impulse response functions that resemble the impulse responses in our empirical model. Specifically, we examine the impact of a 10% energy price increase in our theoretical model when the previous period's energy price is set to its average value in the NOPI regime rather than to its steady-state value. The first step to calculate the average real energy price in the NOPI regime is to identify the NOPI periods using the energy price data outlined in Section 2.2. Next, the nominal energy price is divided by the Core PCE deflator. The resulting real energy price series is then linearly detrended by its average growth rate over the sample period. Using this procedure, the average real energy price is 46.6% above its steady state in NOPI periods from 1972Q1-2018Q1.

Figure 9 displays the simulated model impulse response functions to a 10% energy price increase when the prior period's energy price is 46.6% above its steady state for both the downward rigid nominal wages model and the flexible nominal wages model.[20] Since the previous period's energy price is sufficiently above its steady state, the downward rigid nominal wage constraint is initially binding in the downward rigid nominal wages model, which impacts the expected values of the model's impulse responses. We address that issue by simulating our theoretical model's impulse response functions over 1,000 times and then presenting the averages of those impulse responses.[21] In the simulation, we set the standard deviation of the energy price shock, σ_e, to 0.257. That value is consistent with the standard deviation of the detrended real energy price calculated from the data described in the previous paragraph and our assumption that the persistence of the real energy price, ρ_e, is 0.95.[22]

The impulse response functions in Figure 9 reveal a 10% energy price shock in period t when $p^e_{t-1} = 0.466$ has mostly the same qualitative effects as our impulse responses in Figure 5, except the magnitude of those responses are much smaller. The key exception is in the behavior of the nominal wage rate. Given that the energy price is elevated substantially prior to the energy price shock, the upward tick in the inflation rate is much more muted and dominated by the decline in the real wage. Therefore, the energy price shock causes the nominal wage initially to fall in the flexible nominal wages model, while the nominal wage immediately bumps into its downward constraint in the downward rigid nominal wages

[20] We assume all of the other state variables are at their steady states.

[21] An alternative strategy is to calculate the generalized impulse response functions for our theoretical model when the prior period's energy price is 46.6% above its steady state. The qualitative results from the generalized impulse response functions are similar to the results from our simulated impulse response functions.

[22] Using the detrended real energy price data, we calculate $var(p^E_t) = 0.677$. Thus, $\sigma_e = [var(p^E_t) \times (1 - \rho_e^2)]^{1/2} = 0.257$.

model. The impulse responses in Figure 9, which are designed to more closely approximate the NOPI model, provide further support for our assertion that the presence of downward rigid nominal wages is a plausible theoretical explanation for the empirical effects of an oil price shock produced by Hamilton's (1996, 2003, 2011) NOPI model.

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Table 1: The Data (Mnemonics)

Producer Price Index by Commodity for Fuels and Related Products and Power: Crude Petroleum (WPU0561)
Real Gross Domestic Product (GDPC1)
Industrial Production (INDPRO)
Industrial Production: Durable Manufacturing (IPDMAN)
Hourly Earnings: Private Sector for the United States (LCEAPR01USQ189S)
Nonfarm Business Sector: Average Weekly Hours (PRS85006022)
Real Gross Private Domestic Investment: Fixed Investment (A007RL1Q225SBEA)
Real Gross Private Domestic Investment: Fixed Investment: Residential (A011RL1Q225SBEA)
Real Gross Private Domestic Investment: Fixed Investment: Nonresidential (A008RL1Q225SBEA).
Real Private Fixed Investment: Nonresidential: Structures: Mining Exploration, Shafts, and Wells (E318RL1Q225SBEA)
Real Personal Consumption Expenditures (DPCERL1Q225SBEA)
Real Personal Consumption Expenditures Excluding Food and Energy (DPCCRL1Q225SBEA)
Personal Consumption Expenditures: Chain-type Price Index Less Food and Energy (JCXFE)

Table 2: Calibrated Parameter Values

Parameter	Symbol	Value
Discount factor	β	0.99
Habit persistence in consumption	ϕ_c	0.7
Degree of downward nominal wage rigidity	γ	1
Steady-state labor	n^*	0.3
Frisch labor supply elasticity	$1/\zeta$	0.72
Price elasticity of demand	ϵ	6
Depreciation rate	δ	0.025
Investment adjustment costs parameter	κ	2.5
Capital and energy's share in production	α	0.33
Probability of non-optimal price adjustment	η	0.75
CES consumption/energy substitution parameter	υ_h	-0.9
CES capital/energy substitution parameter	υ_f	-0.9
Energy's share used in consumption	e_h/c	0.043
Energy's share in production	a	0.038
Monetary policy's reaction to inflation	θ_π	1.5
Monetary policy's reaction to output	θ_y	0.125
Monetary policy's reaction to lagged nominal rate	θ_R	0.7
Steady-state gross core inflation rate	π_n^*	1.005
AR coefficient in the energy price shock	ρ_e	0.95

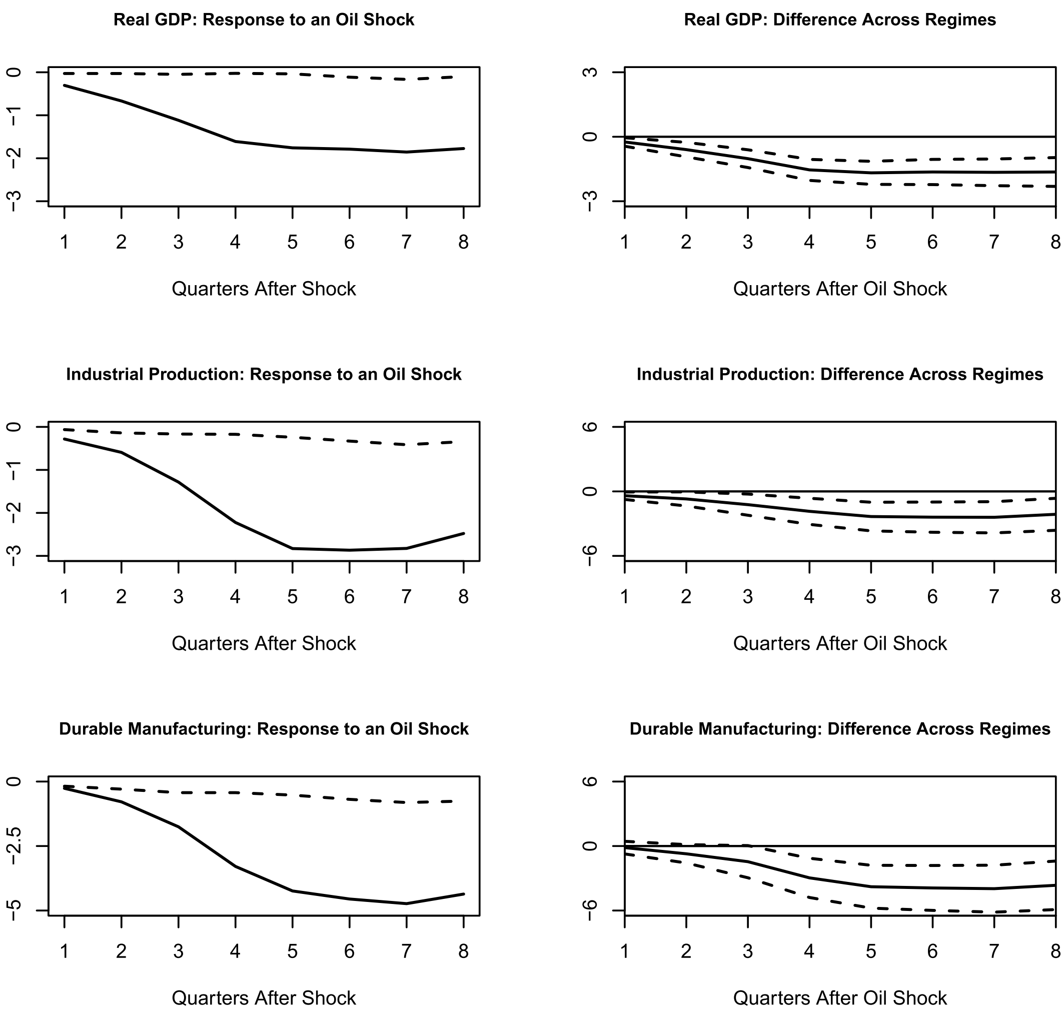

Figure 1: Responses of Output to an Oil Price Shock

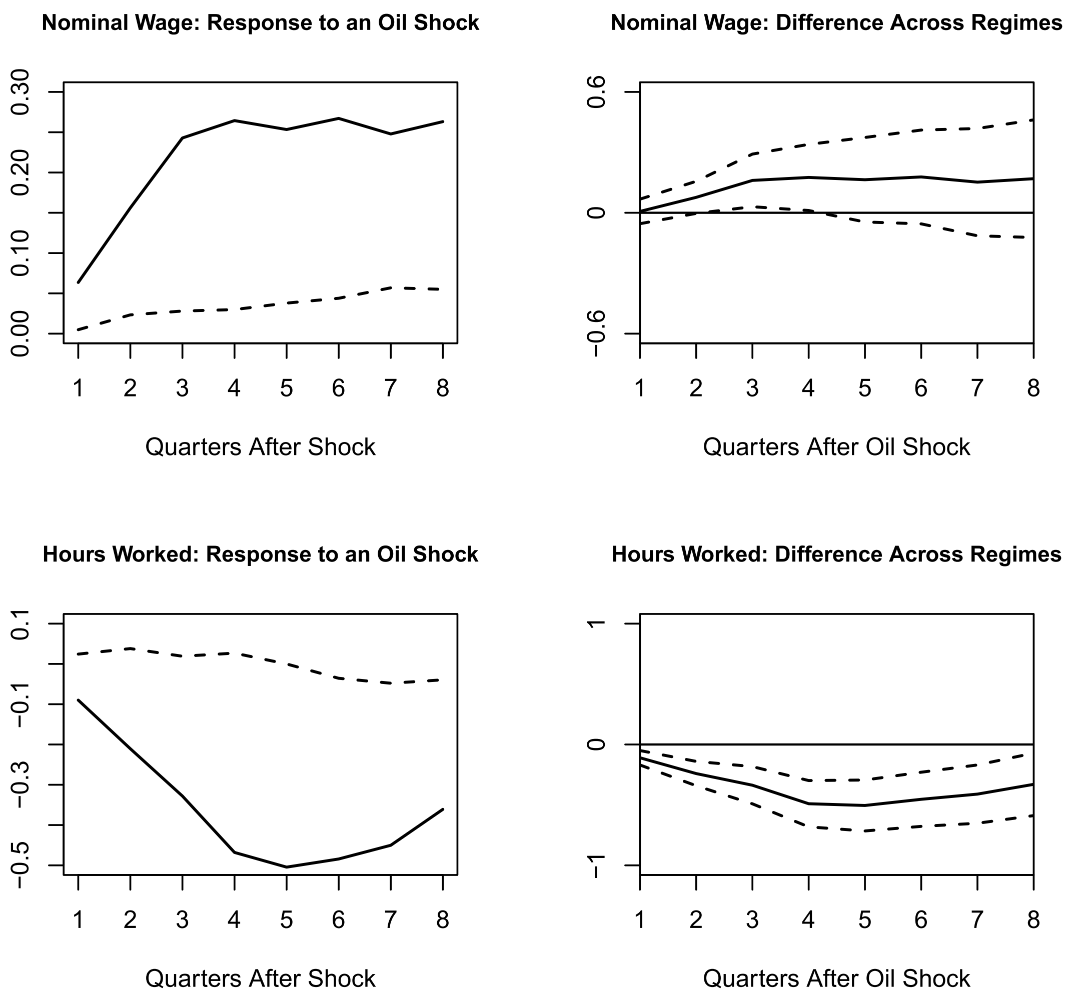

Figure 2: Responses of Labor Market Variables to an Oil Price Shock

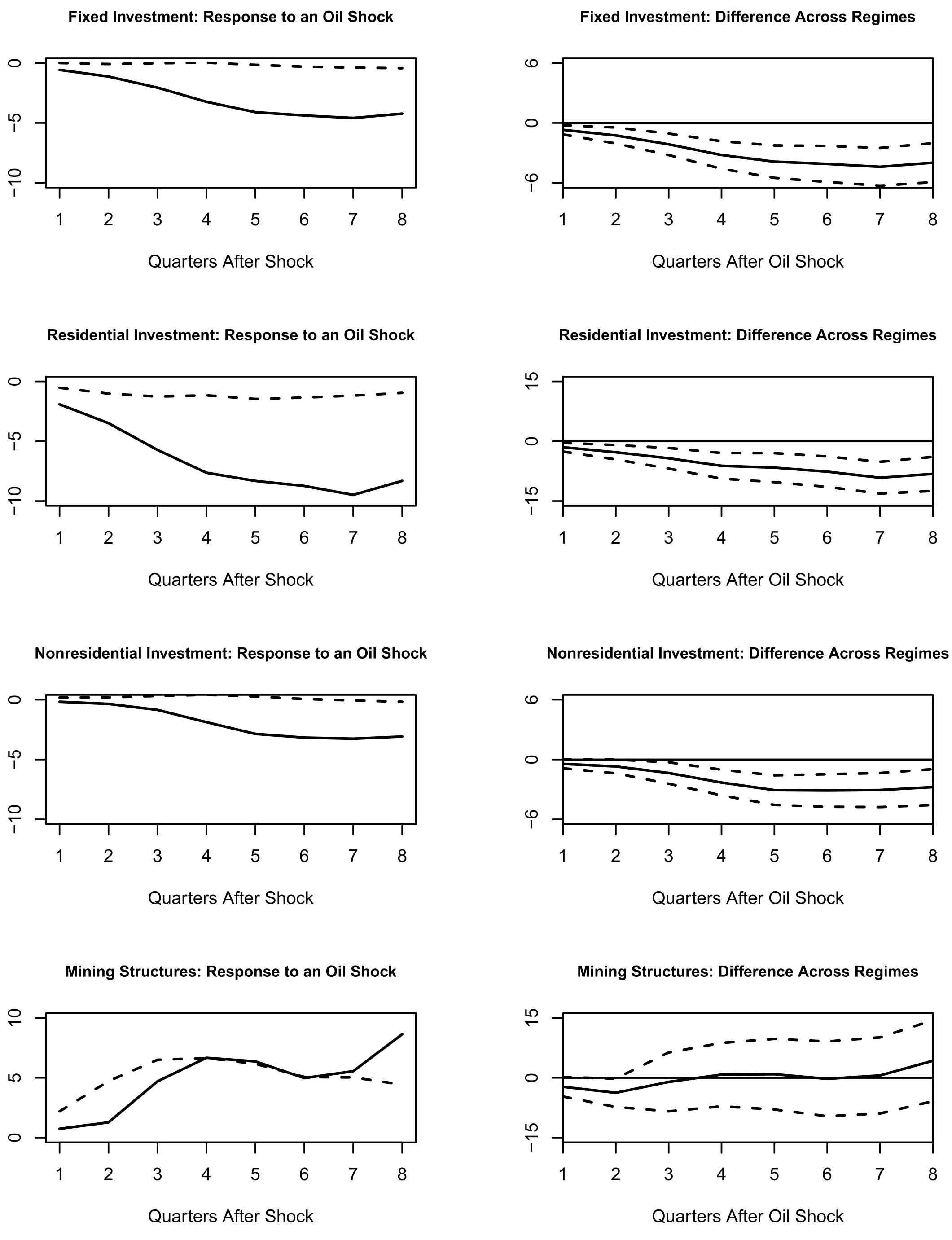

Figure 3: Responses of Investment to an Oil Price Shock

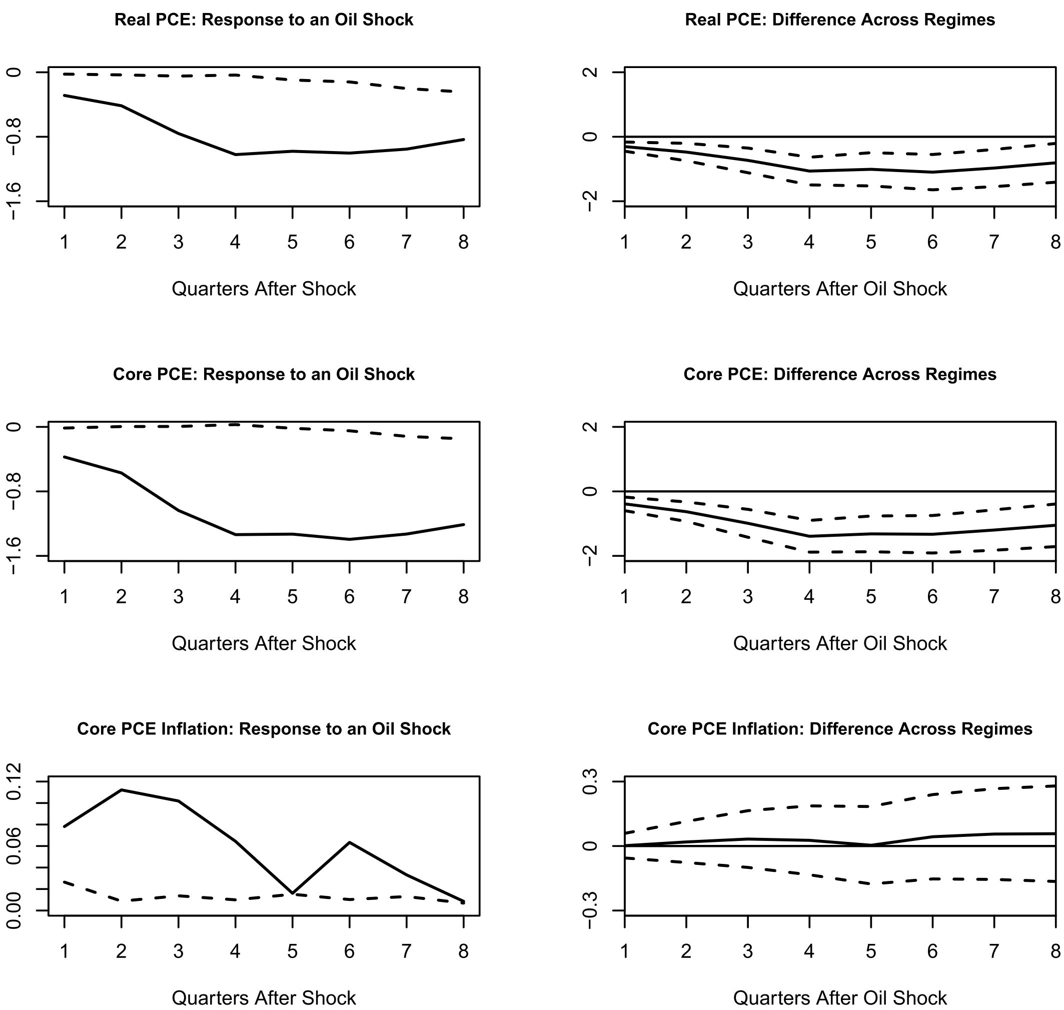

Figure 4: Responses of Consumption and Inflation to an Oil Price Shock

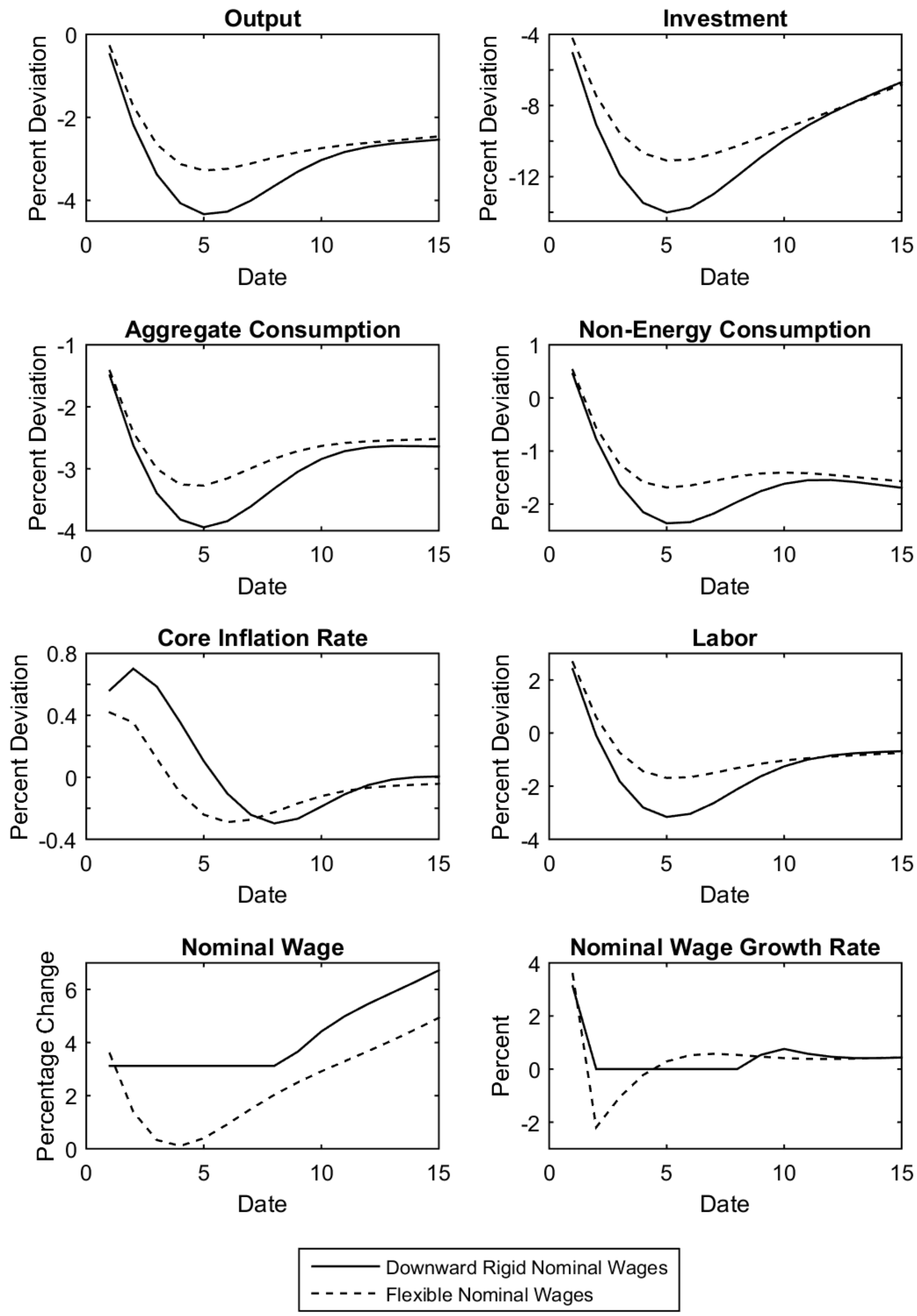

Figure 5: Impulse Responses to an 80% Energy Price Increase

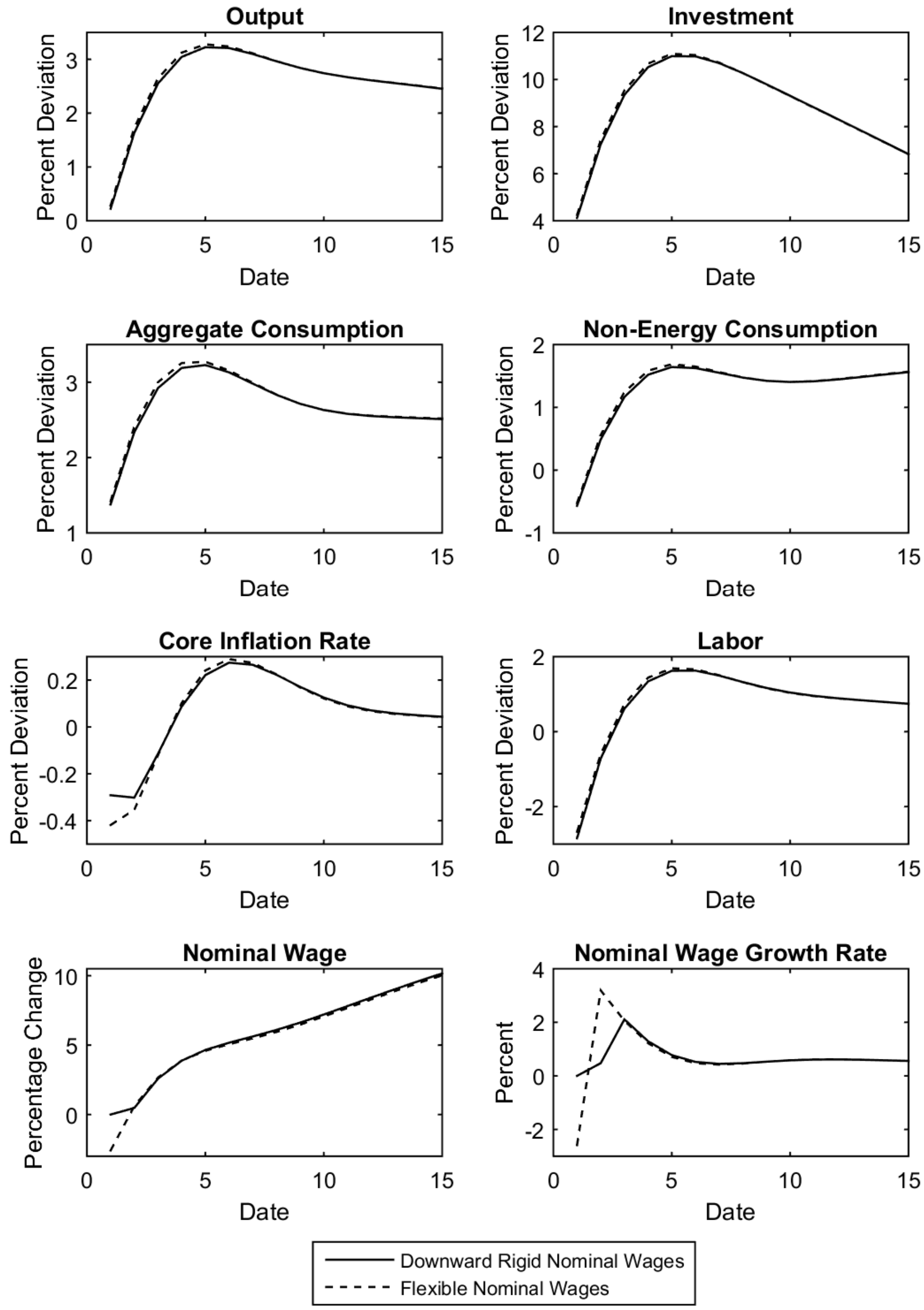

Figure 6: Impulse Responses to an 80% Energy Price Decrease

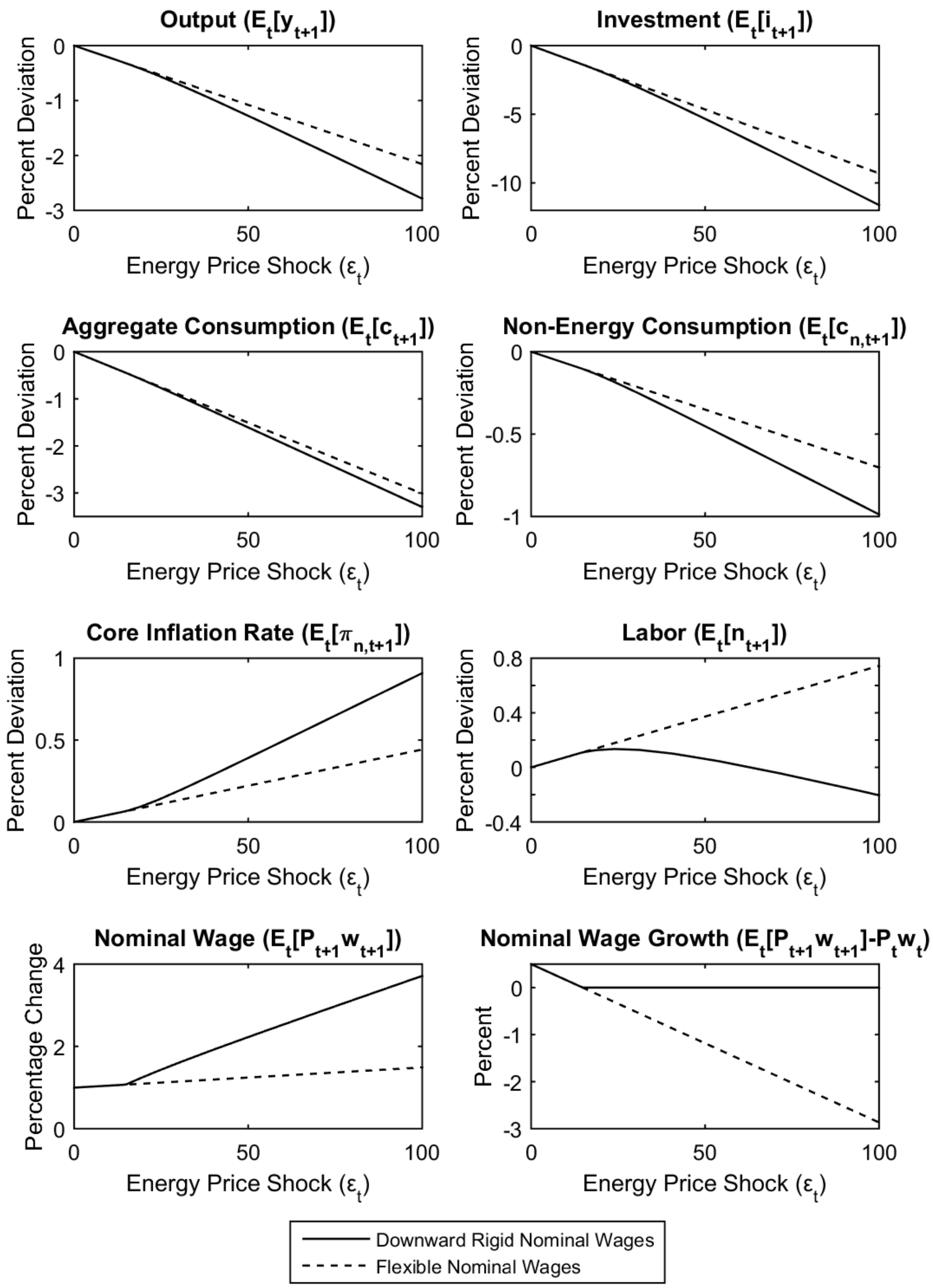

Figure 7: Period $t+1$ Decision Rules as a Function of the Energy Price Shock (ε_t)

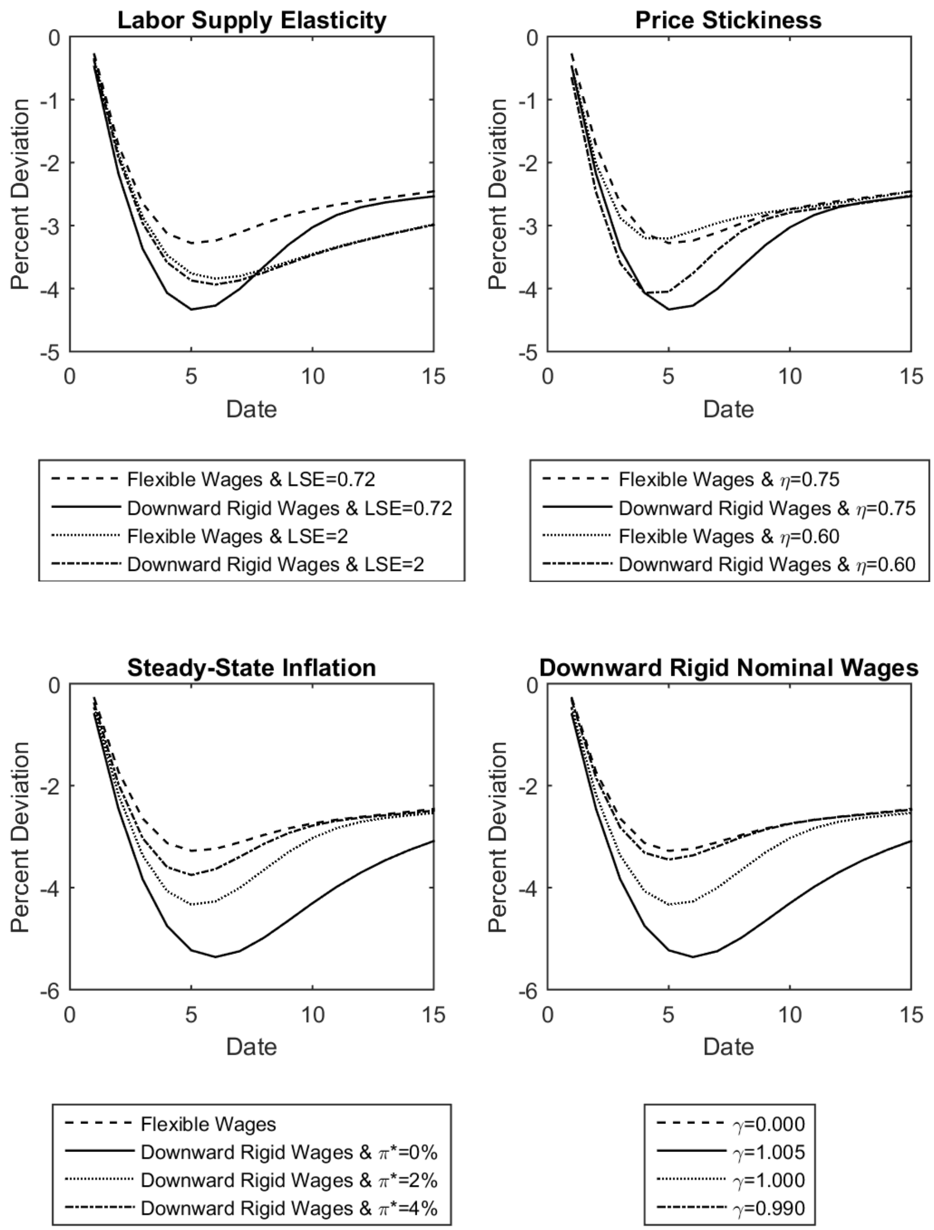

Figure 8: Response of Output to an 80% Energy Price Increase: A Sensitivity Analysis

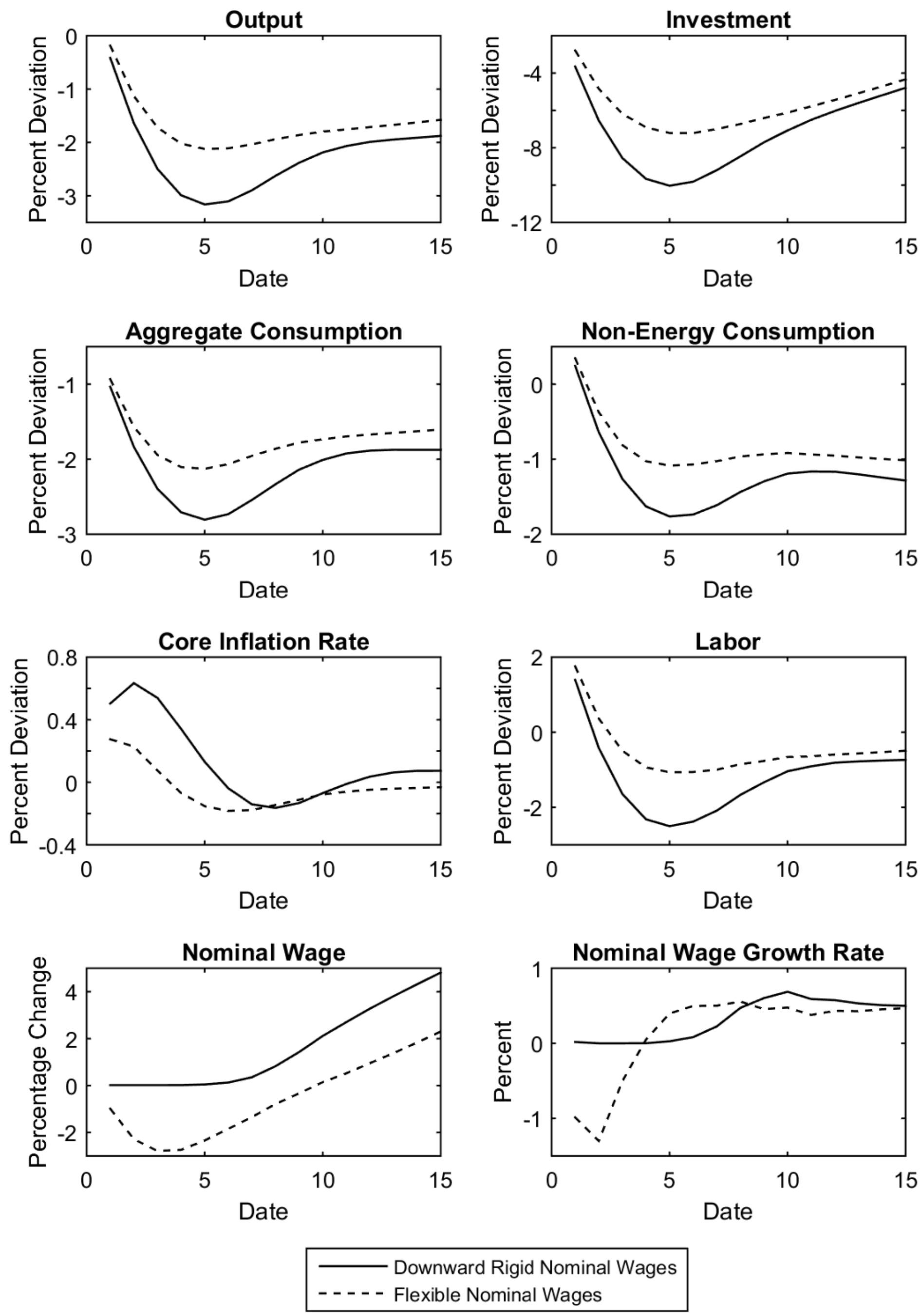

Figure 9: Simulated Impulse Responses to a 10% Energy Price Increase when the Previous Period's Energy Price is 46.6% Above its Steady State ($p_t^e = 0.466$)