Modeling the Asymmetric Effects of an Oil Price Shock*

Lance J. Bachmeier[a] and Benjamin D. Keen[b]
[a]Kansas State University
[b]University of Oklahoma

This paper documents that an oil price increase generates a larger decline in output when the oil price hits a near-term high. We develop a New Keynesian model with energy and a downward nominal wage rigidity that generates asymmetric responses of the macroeconomy to energy price shocks. Specifically, 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 reduce their output further. Since that mechanism is unimportant when energy prices fall, the downward nominal wage constraint causes output to react asymmetrically to oil price shocks.

JEL Codes: E32, Q43.

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

---

*We would like to thank Nathan Balke, James MacGee, Nida Cakir Melek, Michael Plante, Martin Seneca, Martin Stuermer, and Robert Vigfusson for many helpful discussions and comments. The paper also benefited from comments by seminar and conference participants at the Bank of Finland, Colgate University, Federal Reserve Bank of Dallas, Federal Reserve Bank of Kansas City, University of Nevada-Reno, Wichita State University, 2017 Southern Economic Association Meetings, 2018 International Conference on Computing in Economics and Finance, 2019 Society for Nonlinear Dynamics and Econometrics Symposium, and 2019 International Journal of Central Banking Research Conference. Author Contact: Lance J. Bachmeier, Department of Economics, Kansas State University, Waters Hall 321, Manhattan, KS 66506. Tel: (785) 532-4578. E-mail: LanceB@ksu.edu. Benjamin D. Keen, Department of Economics, University of Oklahoma, 308 Cate Center Drive, 437 Cate Center One, Norman, OK 73019. Tel: (405) 325-5900. E-mail: ben.keen@ou.edu.

[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

that models with asymmetry or another form of non-linearity 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" model and Kilian and Vigfusson's (2013) "net oil price change" model. The net oil price increase 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] In contrast, the net oil price change model claims that a change in oil prices generates a larger shift in output when the price of oil hits either a near-term high or a near-term low relative to its recent history. In previous theoretical research, oil price shocks were unable to generate an output response consistent with either the net oil price increase model or the net oil price change model. This paper develops a New Keynesian model with energy and a downward nominal wage rigidity. A particularly interesting result of our model is that output responds asymmetrically to an energy price shock. Specifically, a large energy price increase has a greater effect on output than a large energy price decrease of the same magnitude.

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, such as 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 the price change. Hamilton (1988) argues that capital and labor cannot costlessly move from the sectors that experience a decline in demand to the sectors that experience an increase in demand. That lack of mobility means output will definitely fall after an oil price increase, and it may even fall after an oil price decrease (Hamilton 2003). Although Mork (1989) finds some

---

(2011), and Aastveit (2014). Papers that have worked with theoretical models of the effects of oil price shocks similar to this paper include Bodenstein, Erceg, and Guerrieri (2008), Dhawan and Jeske (2008), Blanchard and Gali (2010), Dhawan, Jeske, and Silos (2010), Blanchard and Riggi (2013), Bodenstein, Guerrieri, and Gust (2013), Plante (2014), Gavin, Keen, and Kydland (2015), Balke and Brown (2018), and Drechsel and Tenreyro (2018).

[2] Hamilton (2003) finds that comparing the current oil price with its values over the previous three years fits the data best.

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 for the substitutability of the factors of production once capital is installed, which means Wei's 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 a two-regime model in which the economy is in the "high oil price regime" when the price of oil hits a near-term high but is otherwise in the "normal oil price regime."[3] Our results show that an oil price increase reduces output more in the high oil price regime than in the normal oil price regime. An oil price increase in the high oil price regime also affects the labor market by generating higher nominal wages and lower hours worked. In the goods market, consumption, business fixed investment, and non-residential investment all decline more rapidly following an oil price increase in the high oil price regime rather than in the normal oil price regime.

This paper develops a New Keynesian model with downward rigid nominal wages in which an energy price increase generates asymmetric effects in the goods and labor markets consistent with our empirical observations.[4] 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 needed to generate asymmetric effects after a large 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 labor demand. Higher energy

---

[3] Our choice of a non-linear and asymmetric specification for the empirical model is motivated by the theoretical model developed in Section 3.

[4] 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), Abbritti and Fahr (2013), Abo-Zaid (2013), Schmitt-Grohe and Uribe (2016), and Baqaee (2020).

costs also decrease households' demand for energy, consumption, and investment, but they increase households' supply of labor. The reduction in labor demand combined with the increase in labor supply puts downward pressure on real and nominal wages. When the pressure is strong enough, the nominal wage hits its downward constraint and is unable to decline any further. Firms respond by reducing their labor demand and output by more than they would have in a flexible wage economy. As a result, a New Keynesian model with downward rigid nominal wages generates asymmetric effects after a large energy price increase. It is important to understand that the presence of the downward nominal wage rigidity is not, by itself, sufficient to generate asymmetric responses to energy price shocks. An energy price shock will only produce asymmetric responses when the downward nominal wage rigidity binds. If the energy price is at or below its steady state, a small increase in energy prices will not produce asymmetric effects because the decline in the real wage is not large enough to cause the downward nominal wage rigidity to bind.[5]

The paper proceeds as follows. Section 2 describes the data, methodology, and impulse response functions for key variables after an oil price shock in both the high and normal oil price regimes. Section 3 presents our theoretical model. Section 4 discusses the calibration and the solution technique for our theoretical model. 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 parameters, compares the effects of an energy price shock in the 1970s with that in the 2000s, and discusses the differences in the effects of an energy price shock caused by foreign demand and supply shocks. Section 6 concludes.

2. Stylized Facts

This section documents the observed effects of oil price shocks on key economic variables that any plausible theoretical model of the

---

[5] This statement assumes that the steady-state headline inflation rate, π^*, is greater than the degree of the downward nominal wage rigidity, γ, (see Equation (6)). If, on the other hand, γ equals π^*, then the model will generate asymmetric effects even following a small energy price increase.

transmission of oil price shocks to the macroeconomy should be able to replicate. Specifically, we show that large oil price increases that push oil prices to near-term highs have a much greater relative impact on output than other oil price shocks. The logic behind this asymmetry is that firms and households often adjust their behaviors only when the price of oil hits levels it has not reached in recent years. Those same firms and households, however, are prepared to manage the expected day-to-day fluctuations that characterize the price of oil, so daily changes have minimal economic impact.

Hamilton's (1996, 2003, 2011) net oil price increase model argues that the difference between the current oil price, oil_t, and the highest oil price in the last 12 quarters, $\widetilde{oil}_t = \max(oil_{t-1}, \ldots, oil_{t-12})$, has a larger impact on economic activity when the current price of oil rises above its three-year high, $oil_t > \widetilde{oil}_t$. Such a specification is a transformation that eliminates most of the variation of the oil price series. Applying the logic of Blanchard and Gali (2010), a downward rigid nominal wage constraint causes non-linearity similar to the net oil price increase model, but it does not transform the oil price data. The Blanchard and Gali model argues that firms respond to a rise in the oil price by reducing output and wages. If nominal wages are bound by a constraint that prevents them from falling, then firms are forced to cut output further.

Our empirical model defines the economy to be in the *high oil price regime* if $oil_t > \widetilde{oil}_t$ and in the *normal oil price regime* if $oil_t \leq \widetilde{oil}_t$. We set the dummy variable $high_t$ equal to 1 in the high oil price regime and equal to 0 in the normal oil price regime. Since the value of $high_t$ depends on the size of oil_t relative to $\widetilde{oil}_t$, $high_t$ is effectively a threshold dummy variable that introduces non-linearity into the model. The dummy variable interacts with the price of oil, $H_t = high_t \Delta oil_t$, to measure the additional impact of an oil price increase in the high oil price regime compared with the same-sized increase in the normal oil price regime. Thus, $H_t > 0$ in the high oil price regime, whereas $H_t = 0$ in the normal oil price regime.[6]

---

[6] Our model is not the same as Hamilton's (1996, 2003, 2011) net oil price increase model. Although we use Hamilton's measure to classify the oil price regime as a high or normal regime, we do not apply his non-linear transformation to the oil price series. The difference is in the calculation of the oil shock in the high oil price regime. Hamilton's oil shock is the percentage change of the

Figure 1 plots separately the oil price changes in the high oil price regime, $high_t = 1$, and the normal oil price regime, $high_t = 0$, from 1972:Q2 through 2017:Q4.[7] The economy is in the high oil price regime for 30 percent of the time and in the normal oil price regime for the remaining periods. Our focus is on the large oil price increases in the high oil price regime because those shocks can have a substantial effect on output. Figure 1 reveals that oil prices rose swiftly above their recent highs in 1973–74, 1979–80, 1981, 1990, and the early 2000s, with each period being followed by a recession. The first four oil price increases are usually attributed to foreign oil supply disruptions, while the 2002–08 oil price spike is often credited to higher oil demand from China and India. Most economists believe those negative oil supply shocks were either the primary reason for or a key contributing factor of the 1974–75, 1980, 1981–82, and 1991 recessions, whereas the financial crisis was the primary cause of the 2008 recession, as opposed to the large rise in oil demand. Given that those large oil price increases significantly affected output, our paper estimates the economic effects of large oil price increases and then builds a theoretical model that generates responses to energy price shocks consistent with that behavior.

2.1 Methodology

The threshold dummy variable $high_t$ introduces a non-linearity into our model. We estimate the model using the method of local projections introduced by Jorda (2005). Our empirical analysis then compares the impulse response functions from a 9.5 percent oil price increase in the high oil price regime with the impulse response functions from a 9.5 percent oil price increase in the normal oil price regime.[8] This model differs somewhat from the literature on state-dependent effects of fiscal and monetary policy (e.g., Ramey and Zubairy 2018) in that the variable being shocked also determines the state and therefore changes in regime.

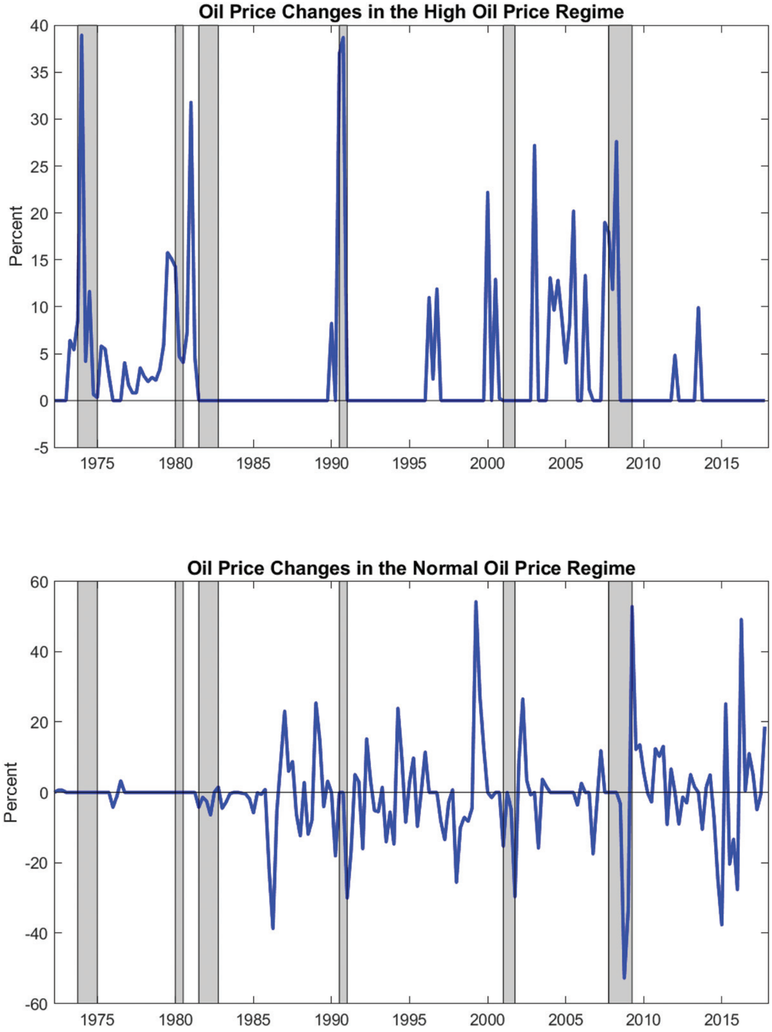
---

current price of oil over the recent maximum price of oil. That comparison is not consistent with the New Keynesian model we present later, so we use the percentage change in the price of oil without doing a transformation.

[7] The oil price data is defined in Section 2.2.

[8] 9.5 percent is the average quarterly increase in the price of oil in the high oil price regime.

Figure 1. Oil Price Changes in the High and Normal Oil Price Regimes



Note: Shaded areas represent recessions. An oil price change of zero indicates either the economy is not in that oil price regime or the oil price was unchanged.

Kilian (2009) and Kilian and Vega (2011) present strong evidence that oil prices are predetermined with respect to current economic conditions.[9] Therefore, we estimate the impact of an oil price change in period $t - s$ on key macroeconomic variables in period t,

$$\Delta x_t = \theta_s + \sum_{i=0}^{p} \delta_{s,i} \Delta oil_{t-s-i} + \sum_{i=0}^{p} \phi_{s,i} H_{t-s-i} + \varepsilon_{s,t}, \qquad (1)$$

where Δx_t is the percentage change in the macroeconomic variable, Δoil_t is the percentage change in the price of oil, and $\varepsilon_{s,t}$ is the error term.[10] A separate estimate of (1) is calculated for each forecast horizon, s, where $s = 0, \ldots, 8$. At each horizon s, the estimated values $\widehat{\delta}_{s,0}$ and $\widehat{\phi}_{s,0}$ are multiplied by $\Delta oil^H_{t-s} = 0.095$ and $H^H_{t-s} = 0.095$ in the high oil price regime and $\Delta oil^N_{t-s} = 0.095$ and $H^N_{t-s} = 0$ in the normal oil price regime to generate the s-period impulse response for $\Delta \widehat{x}^H_{t,s}$ in the high oil price regime and $\Delta \widehat{x}^N_{t,s}$ in the normal oil price regime, respectively. We then calculate the s-period cumulative impulse response functions, $CR_{t+s} = \sum_{j=0}^{s} \Delta \widehat{x}_{t,j}$, to present all of the variables, except the inflation rate, in level form.[11]

We are interested in determining whether oil price shocks affect key economic variables symmetrically, $\widehat{\phi}_{s,0} = 0$, or asymmetrically, $\widehat{\phi}_{s,0} \neq 0$. In the case of symmetry, the cumulative impulse response functions from an oil price increase in the high oil price regime, CR^H_{t+s}, are equal to the cumulative impulse response functions from an oil price increase in the normal oil price regime, CR^N_{t+s}. Oil price shocks, however, have asymmetric effects in the high oil price regime

---

[9] We also assume that the state of oil prices is predetermined with respect to economic conditions.

[10] We use the current value and three lags of the oil price as controls, so oil price data from the last full year affect the macroeconomic variables. Since there is no clear procedure to choose the number of lags when using Jorda's (2005) method of local projections, we select enough lags to capture the predictable effects of oil price shocks, while avoiding inefficient estimation by including too many lags. Proper lag selection requires a model of Δoil_t to obtain the best possible identification of the oil shock. An advantage of the local projections method is that it does not require a fully specified structural VAR model.

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

when there is a significant difference between the cumulative impulse response functions CR^H_{t+s} and CR^N_{t+s}. That is, the cumulative difference function, $CD_{t+s} = CR^H_{t+s} - CR^N_{t+s}$, is significantly different than zero. To determine if oil price shocks have asymmetric effects, we construct the 95 percent confidence intervals for the cumulative difference functions by using the fact that H_{t-s} is the only regressor that is different in the two regimes (i.e., $H^H_{t-s} = 0.095$ and $H^N_{t-s} = 0$). Specifically, we multiply the heteroskedasticity and autocorrelation consistent (HAC) standard errors on $\widehat{\phi}_{s,0}$ by H^H_{t-s} to get the standard errors for the differences in the impulse response functions, $\Delta x^H_{t+s} - \Delta x^N_{t+s}$. The standard errors for $\Delta x^H_{t+s} - \Delta x^N_{t+s}$ are combined using the delta method to generate the standard errors for the cumulative difference functions and their resulting 95 percent confidence intervals.[12]

2.2 Data

Table 1 displays the data and their mnemonics. Each of the 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 1972:Q1–2018:Q1. That sample period was chosen to avoid the inflated effects of oil price shocks when using data prior to the early 1970s.[13]

2.3 Empirical Impulse Response Functions

Figures 2 through 5 present the cumulative impulse response functions and the cumulative difference functions for output, wages, hours worked, investment, consumption, and inflation following a

---

[12] The covariances of coefficients across equations are ignored due to the difficulty of correcting for serial correlation when using multiple values of s in the same system. We did, however, apply a pairs bootstrap to compute the cross-equation covariances. The change has no meaningful impact on the results because the off-diagonal elements of the covariance matrix are much smaller in magnitude than the variance terms.

[13] See Herrera, Lagalo, and Wada (2011).

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)
Average Hourly Earnings of Production and Non-supervisory Employees: Manufacturing (CES3000000008)
Non-farm Business Sector: Average Weekly Hours (PRS85006022)
Average Weekly Hours of Production and Non-supervisory Employees: Manufacturing (AWHMAN)
Real Gross Private Domestic Investment: Fixed Investment (A007RL1Q225SBEA)
Real Gross Private Domestic Investment: Fixed Investment: Residential (A011RL1Q225SBEA)
Real Gross Private Domestic Investment: Fixed Investment: Non-residential (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)
Personal Consumption Expenditures: Chain-type Price Index (PCECTPI)

9.5 percent oil price increase.[14] In the left-hand column of each figure, the solid lines represent the cumulative impulse responses from the oil price shock in the high oil price regime, and the dashed lines display the cumulative responses following the same shock in the normal oil price regime. In the right-hand column of each figure, the solid line represents the cumulative difference functions, and the dashed lines show their 95 percent confidence intervals.

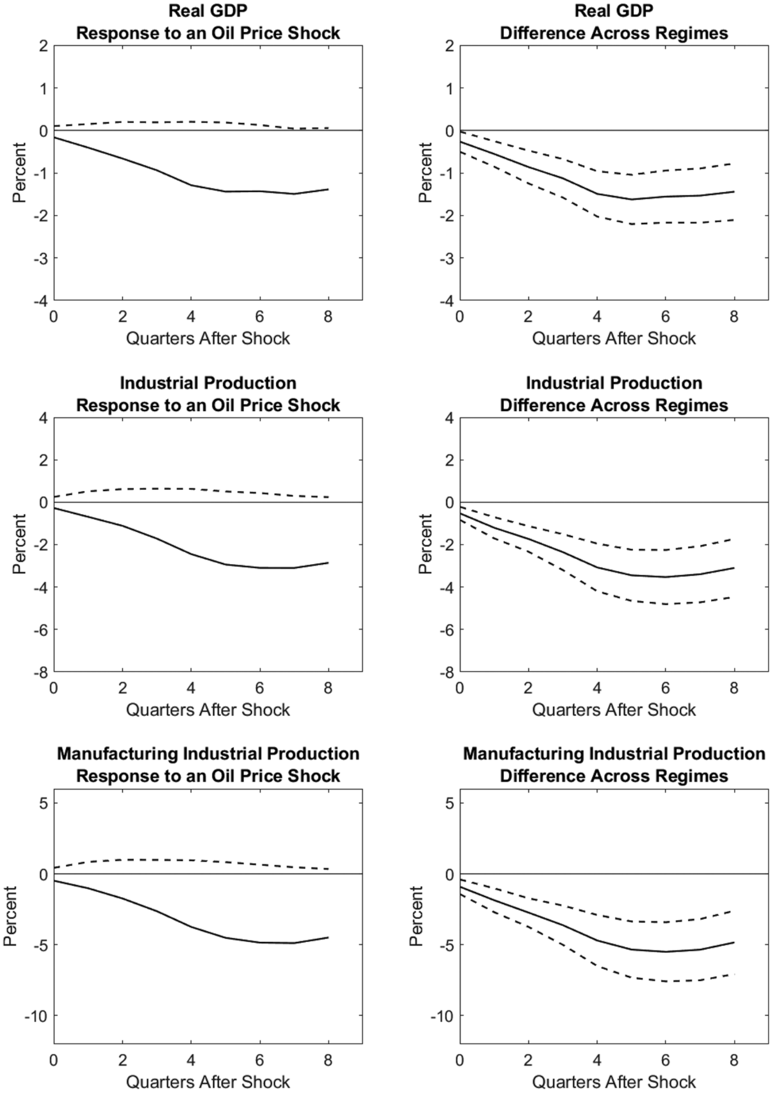
2.3.1 Response of Output

Figure 2 shows that gross domestic product (GDP), industrial production, and durable goods manufacturing decline significantly more after an oil price increase in the high oil price regime than in the

---

[14] The impulse responses for the inflation rate in Figure 5 are the standard impulse response functions and not the cumulative impulse response functions.

Figure 2. Responses of Output to an Oil Price Shock



Note: The left-hand column shows the responses to a 9.5 percent oil price increase in the high oil price regime (solid line) and the normal oil price regime (dashed line). The right-hand column shows the difference in the responses (solid line) and their 95 percent confidence bands (dashed lines), where negative values imply that the responses in the high oil price regime are less than the responses in the normal oil price regime.

normal oil price regime. A 9.5 percent oil price increase[15] in the high oil price regime is followed by a cumulative reduction in real GDP of 1.3 percentage points over the next year. In our sample period, real GDP grew on average 2.7 percent per year, so although a 9.5 percent oil price increase probably would not cause a recession, it would be followed by a noticeable slowdown in output growth. In contrast, a 9.5 percent increase in the oil price has a very modest effect on real GDP in the normal oil price regime. Industrial production is a measure of output in manufacturing, mining, and electric and gas utilities. In the high oil price regime, a 9.5 percent oil price increase pushes down industrial production by 2.4 percentage points after one year. A 9.5 percent increase in oil prices, however, only generates a slight increase in industrial production in the normal oil price regime.

A substantial rise in oil prices is expected to affect manufacturing more negatively than the economy as a whole due to manufacturing's greater reliance on energy. 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 reasons, we examine the impact of an oil price shock on the manufacturing of durable goods.[16] In the high oil price regime, durable goods manufacturing falls by nearly 3.75 percentage points in the first year after the 9.5 percent oil price increase and continues to decline in year 2. The impulse responses reveal durable goods manufacturing increases by a very small amount after a 9.5 percent rise in oil prices in the normal oil price regime.

2.3.2 Labor Market Variables

Blanchard and Gali (2010) find that oil price shocks have a smaller effect on output when wages are flexible than when wages are sticky

---

[15] Recall, the average quarterly oil price increase in the high oil price regime is 9.5 percent.

[16] The manufacturing of durable goods represented 38 percent of total industrial production in 2012. According to Federal Reserve Board data release notes, durable goods manufacturing includes the following categories of production: wood product; non-metallic 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.

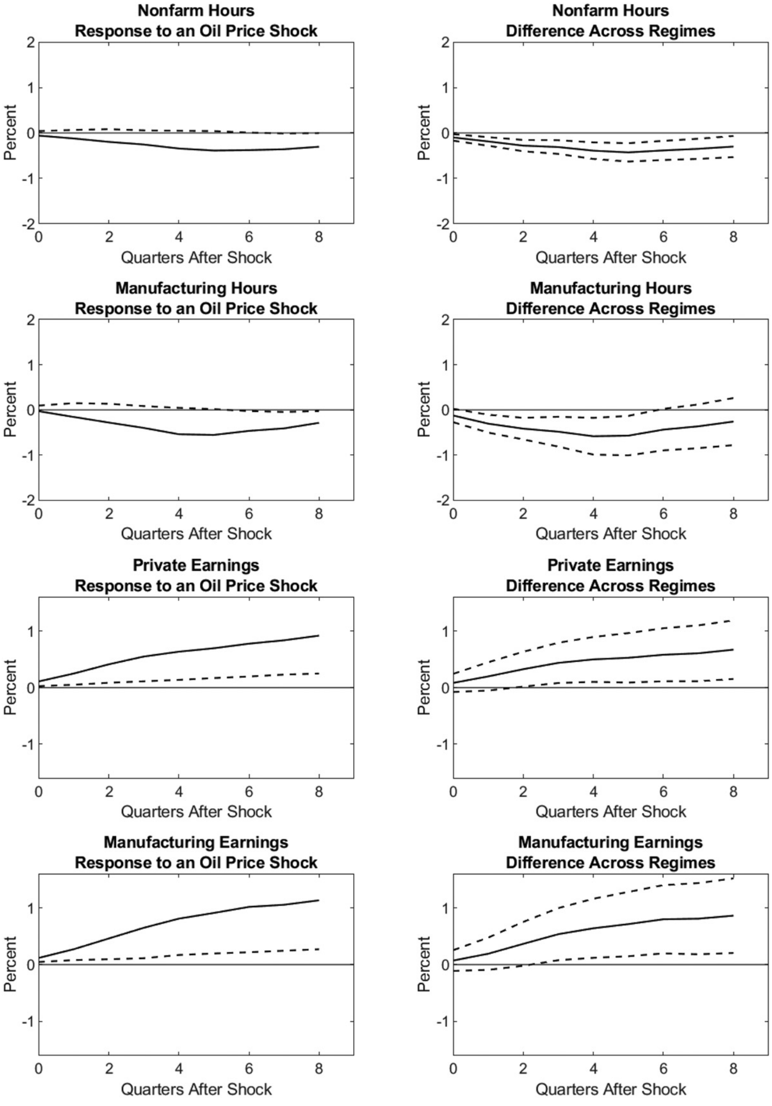
or rigid. Specifically, an economy with flexible wages produces a larger drop in the real wage rate after an oil price increase, which puts more downward pressure on the real marginal cost. That downward pressure mitigates some of the rise in the marginal cost caused by the higher oil price and, as a result, limits the decline in output. Figure 3 shows the impact of an oil price shock on weekly hours worked (non-farm hours and manufacturing hours) and hourly nominal wages (private earnings and the manufacturing earnings). Non-farm hours and manufacturing hours fall by nearly 0.26 and 0.40 percentage point, respectively, in the first year after a 9.5 percent oil price increase in the high oil price regime, which are significantly greater than their responses in the normal oil price regime. That same 9.5 percent oil price increase also pushes up private earnings and manufacturing earnings in the first year by 0.55 and 0.65 percentage point, respectively, in the high oil price regime, but those same variables increase by 0.11 percentage point in the normal oil price regime, which is consistent with Blanchard and Gali's theoretical model.

A discrepancy exists between our empirical model and the theoretical model presented in Section 3. The nominal wage initially rises and then remains flat for several periods in the theoretical model, but the nominal wage rises continuously in the empirical model. The difference is explained by the fact that our empirical model is estimated over a period with both substantial nominal wage indexation to inflation (the 1970s) and little nominal wage indexation to inflation (post-1982).[17] When wages are indexed to inflation, higher inflation caused by an oil price increase automatically pushes up the lower bound on the nominal wage. That higher lower bound leads to an upward drift in nominal wages, which is consistent with our empirical results. In the absence of wage indexation, inflation does not automatically raise the lower bound on nominal wages. When our empirical model is estimated starting in 1983:Q1 instead of 1972:Q1, the one-year increases in private earnings and manufacturing earnings are only 0.17 and 0.09 percentage point, respectively, in the high oil price regime, while both one-year responses are

---

[17] Using an estimated New Keynesian model, Keen and Koenig (2018) find that the degree of wage indexation to inflation in the United States is much higher in the 1960s and 1970s than in the post-1982 period.

Figure 3. Responses of Labor Market Variables to an Oil Price Shock



Note: The left-hand column shows the responses to a 9.5 percent oil price increase in the high oil price regime (solid line) and the normal oil price regime (dashed line). The right-hand column shows the difference in the responses (solid line) and their 95 percent confidence bands (dashed lines), where negative values imply that the responses in the high oil price regime are less than the responses in the normal oil price regime.

essentially zero in the normal price regime.[18] Those results from the post-1982 sample are consistent with the findings from our theoretical model, which is calibrated to values consistent with the Great Moderation (1983–2007).

The model presented in Section 3 assigns a key role to labor market rigidities like in Blanchard and Gali (2010). An important distinction of our model, however, is the focus on downward rigid nominal wages as an explanation for the asymmetric responses generated in the high oil price regime. Blanchard and Gali assume that real wages are sticky, which result in symmetric responses to oil price shocks.

2.3.3 Investment

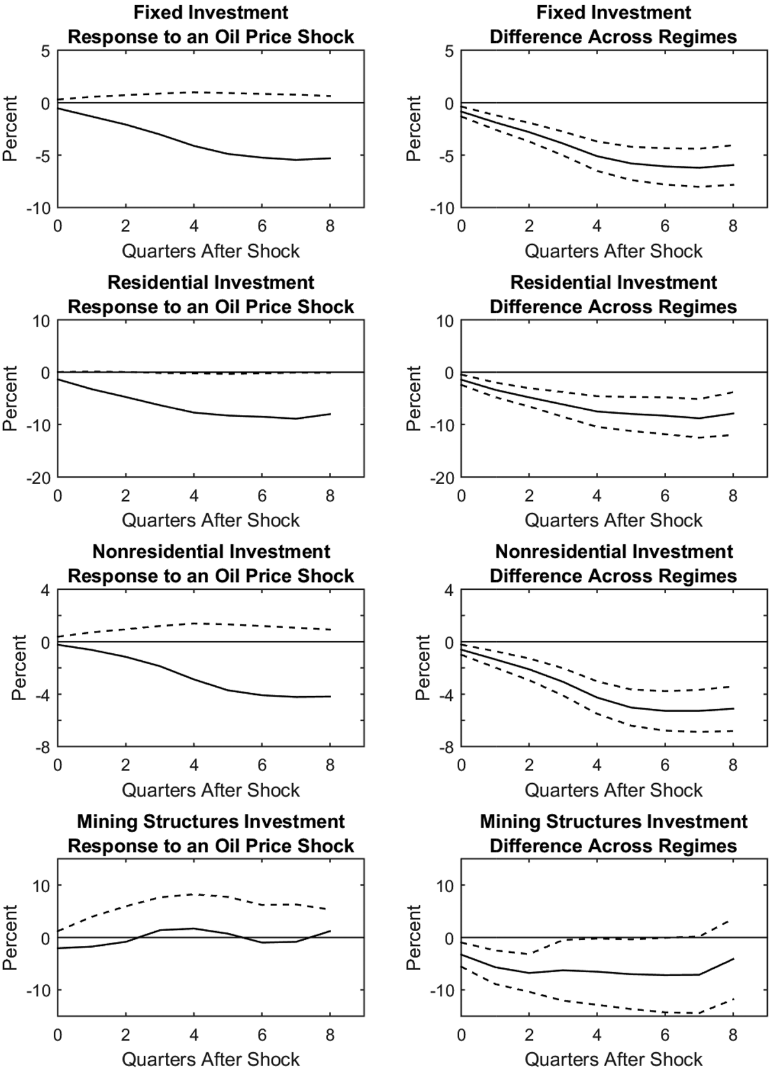
Figure 4 presents the impact of an oil price shock on private fixed investment, residential investment, non-residential investment, and investment in mining structures. A 9.5 percent oil price increase in the high oil price regime produces a significantly larger decline in private fixed investment, residential investment, and non-residential investment than in the normal oil price regime. Private fixed investment falls more than 4 percentage points in the year after a 9.5 percent oil price increase in the high oil price regime, but it slightly rises in the normal oil price regime. That slight increase in private fixed investment after an oil price increase is caused by the fact that higher oil prices usually stimulate energy-related investment.

Residential investment declines much more than aggregate investment after an oil price increase in the high oil price regime. A 9.5 percent oil price increase in the high oil price regime pushes down residential investment by nearly 8 percentage points over the next year, while the same-sized shock causes residential investment to remain essentially unchanged in the normal oil price regime. Non-residential investment declines by about 2.9 percentage points in the year after a 9.5 percent oil price increase in the high oil price regime, with much of that drop due to a large fall in equipment investment. In the normal oil price regime, the same oil price shock has a small positive effect on non-residential investment. That 9.5 percent oil

---

[18] The impulse response functions estimated with data starting in 1983:Q1 are included in the appendix, which is available on the authors' websites.

Figure 4. Responses of Investment to an Oil Price Shock



Note: The left-hand column shows the responses to a 9.5 percent oil price increase in the high oil price regime (solid line) and the normal oil price regime (dashed line). The right-hand column shows the difference in the responses (solid line) and their 95 percent confidence bands (dashed lines), where negative values imply that the responses in the high oil price regime are less than the responses in the normal oil price regime.

price increase also pushes up investment in mining structures by 1.7 percentage points in the high oil price regime and by over 8 percentage points in the normal oil price regime.

2.3.4 Consumption and Inflation

Figure 5 displays the impulse response functions for the high oil price and normal oil price regimes and the difference functions for real personal consumption expenditures (PCE), real core PCE, the PCE inflation rate, and the core PCE inflation rate.[19] A 9.5 percent oil price increase in the high oil price regime causes real PCE and real core PCE to decline by over 1 percentage point in the first year. In contrast, a 9.5 percent increase in oil prices has much more moderate effects on real PCE and real core PCE in the normal oil price regime. As for inflation, PCE inflation initially jumps by 0.32 percent and then gradually declines after a 9.5 percent oil price increase in the high oil price regime. The same shock causes the core PCE inflation rate to rise initially by 0.13 percent in the high oil price regime. That number remains steady for about a year and then slowly declines. The 9.5 percent oil price increase has little effect on either inflation measure in the normal oil price regime. The difference in the responses of PCE inflation and core PCE inflation across the two regimes is not statistically significant.

3. Theoretical Model

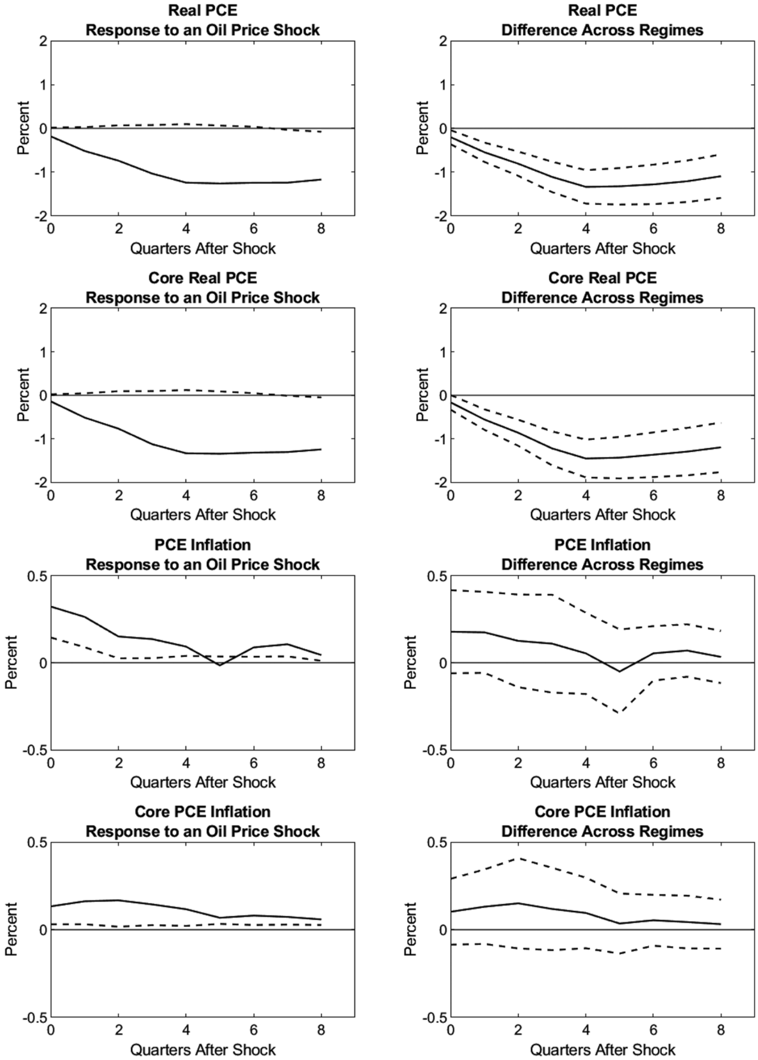
This section develops a New Keynesian model with price stickiness and downward rigid nominal wages to examine the asymmetric effects of key variables to an energy price shock. Price setting follows a Calvo (1983) model of random adjustment, where nominal wages are perfectly flexible on the upside but rigid on the downside. Energy is demanded by households as a consumption good and by firms as a factor of production.[20] The energy endowment each period

---

[19] The impulse response functions and difference functions are cumulative for real PCE and real core PCE, but they are standard (non-cumulative) for PCE inflation and core PCE inflation.

[20] Since energy enters both the households' utility function and the firms' production functions, an energy price shock is equivalent to some combination of

Figure 5. Responses of Consumption and Inflation to an Oil Price Shock



Note: The left-hand column shows the responses to a 9.5 percent oil price increase in the high oil price regime (solid line) and the normal oil price regime (dashed line). The right-hand column shows the difference in the responses (solid line) and their 95 percent confidence bands (dashed lines), where negative values imply that the responses in the high oil price regime are less than the responses in the normal oil price regime.

is sufficient to meet market demand at its exogenously determined price.

The downward nominal wage rigidity is the critical feature in our model that enables energy price shocks to have asymmetric effects. Specifically, a large energy price increase puts downward pressure on real wages, but the downward nominal wage rigidity prevents the nominal wage from falling. That constraint forces firms to reduce both their labor demand and output further, which causes key variables to respond asymmetrically.

Gottschalk (2005), Barattieri, Basu, and Gottschalk (2014), and Hazell and Taska (2018) find evidence in U.S. data that nominal wages are downward rigid. Our model, however, specifically assumes the downward nominal wage rigidity is more likely to bind after a large jump in energy prices. Over the last 40 to 50 years, large oil price increases are considered the primary cause of several U.S. recessions. Daly and Hobijn (2014) and Jo (2021) find evidence that U.S. nominal wages were more rigid during and immediately after those oil-price induced recessions.[21] Their findings support our conjecture that a large energy price increase raises the likelihood the downward nominal wage constraint binds.

3.1 Households

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

---

a demand shock and a supply shock in a traditional three-equation New Keynesian model. Thus, an energy shock in our model differs from Kim and Ruge-Murcia (2009, 2011), Abbritti and Fahr (2013), and Abo-Zaid (2013), where those papers examine how the downward nominal wage rigidity impacts the asymmetric responses of economic variables to a simple supply shock.

[21] Using Current Population Survey (CPS) data for 1986–2014, Daly and Hobijn (2014) find that the share of workers not receiving a nominal wage increase in a particular year rose during and immediately after the 1991 recession. The Federal Reserve Bank of San Francisco's Wage Rigidity Meter finds similar results with CPS data for the 1981–82 and 1991 recessions. Similarly, Jo (2021) finds that the share of workers not receiving a wage increase rises after the 1980, 1981–82, and 1991 recessions using both the CPS and the Survey of Income and Program Participants data. We should note that Daly and Hobijn, Jo, and the San Francisco Fed's Wage Rigidity Meter also find that the share of workers not receiving a wage increase rises after the 2001 and 2008 recessions, but most economists do not believe oil price increases had a major role in those recessions.

$$U = E_t \sum_{j=0}^{\infty} \beta^j \left[\ln \left(c_{t+j} - \phi_c h_{t+j} \right) - \phi_n \frac{n_{t+j}^{1+\zeta} - 1}{1+\zeta} \right], \tag{2}$$

subject to a consumption aggregator, budget constraint, capital equation, and a nominal wage rigidity that prevents 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 $(h_t = c_{t-1})$, $\zeta \geq 0$ is the labor supply elasticity, and $\phi_n > 0$. Aggregate consumption is a constant elasticity of substitution (CES) composite of energy consumption, $e_{h,t}$, and non-energy consumption, $c_{n,t}$,

$$c_t = \left(a_1 e_{h,t}^{\upsilon_h} + a_2 c_{n,t}^{\upsilon_h} \right)^{1/\upsilon_h}, \tag{3}$$

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. As a result, the aggregate price level (headline price level), P_t, is a function of the price of non-energy output (core price level), $P_{n,t}$, and the price of energy, $P_{e,t}$:

$$P_t = \left(a_1^{1/(1-\upsilon_h)} P_{e,t}^{\upsilon_h/(\upsilon_h-1)} + a_2^{1/(1-\upsilon_h)} P_{n,t}^{\upsilon_h/(\upsilon_h-1)} \right)^{(\upsilon_h-1)/\upsilon_h}. \tag{4}$$

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

$$\begin{aligned} &\left(\frac{P_{n,t}}{P_t} \right) (c_{n,t} + i_t) + \left(\frac{P_{e,t}}{P_t} \right) e_{h,t} + b_t \\ &\quad = \frac{R_{t-1} b_{t-1}}{\pi_t} + d_t + w_t n_t + \left(\frac{P_{n,t}}{P_t} \right) q_t k_t. \end{aligned} \tag{5}$$

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 share of profits from firms and the energy sector, d_t, where w_t is the real wage rate, q_t is the real rental rate of capital, and k_t is 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.

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

$$k_{t+1} - k_t = i_t \left(1 - S\left(\frac{i_t}{i_{t-1}}\right)\right) - \delta k_t, \tag{6}$$

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 $S(1) = S'(1) = 0$ and $\kappa = S''(1) > 0$.

Households supply labor in a perfectly competitive market but will not accept a nominal wage below its previous level. Thus, we have the following inequality constraint:

$$P_t w_t \geq \gamma P_{t-1} w_{t-1}, \tag{7}$$

where $\gamma \geq 0$ measures the degree of downward nominal wage rigidity. Nominal wages are absolutely downward rigid when $\gamma \geq 1$ but are perfectly flexible when $\gamma = 0$. During the periods when (6) 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:

$$y_{f,t} = \left(b k_{f,t}^{\upsilon_f} + (1-b) e_{f,t}^{\upsilon_f}\right)^{\alpha/\upsilon_f} (n_{f,t})^{1-\alpha}, \tag{8}$$

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, $P_{n,t}q_t k_{f,t} + P_t w_t n_{f,t} + P_{e,t}e_{f,t}$, subject to (7) to generate its input factor demands.

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

$$y_t = \left[\int_0^1 y_{f,t}^{(\epsilon-1)/\epsilon} df\right]^{\epsilon/(\epsilon-1)}, \tag{9}$$

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 by households means the demand for $y_{f,t}$ is a decreasing function of its relative price:

$$y_{f,t} = \left(\frac{P_{f,t}}{P_{n,t}}\right)^{-\epsilon} y_t, \tag{10}$$

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

$$P_{n,t} = \left[\int_0^1 P_{f,t}^{(1-\epsilon)} df\right]^{1/(1-\epsilon)}. \tag{11}$$

Non-energy output comprises non-energy consumption and investment, $y_t = c_{n,t} + i_t$.

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

$$\max_{P^*_{f,t}} E_t\left[\sum_{j=0}^{\infty}\beta^j\eta^j\lambda_{t+j}\left(\frac{\Pi_{n,t+j}P^*_{f,t}}{P_{t+j}}y_{f,t+j}-w_{t+j}n_{f,t+j}\right.\right.$$
$$\left.\left.-\frac{P_{n,t+j}}{P_{t+j}}q_{t+j}k_{f,t+j}-\frac{P_{e,t+j}}{P_{t+j}}e_{y,t+j}\right)\right], \tag{12}$$

where

$$\Pi_{n,t+j}=\left\{\begin{array}{ll}\pi_{n,t}\times\pi_{n,t+1}\times\cdots\times\pi_{n,t+j-1} & \text{for } j\geq 1\\ 1 & \text{for } j=0\end{array}\right\} \tag{13}$$

subject to the demand for its product, (9), and its input factor demands.

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:

$$e_t = e_{h,t} + e_{f,t}. \tag{14}$$

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

$$\ln(p_{e,t}) = \rho_e \ln(p_{e,t-1}) + \varepsilon_t, \tag{15}$$

where $0 \leq \rho_e < 1$ and $\varepsilon_t \sim N(0, \sigma_e)$.[22]

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

---

[22] 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 price of energy, being exogenous.

the lagged nominal interest rate, R_{t-1}, the core inflation rate, $\pi_{n,t}$, and non-energy output, y_t:

$$\begin{aligned}\ln(R_t/R) &= \theta_R \ln(R_{t-1}/R)\\ &\quad + (1-\theta_R)[\theta_\pi \ln(\pi_{n,t}/\pi_n^*) + \theta_y \ln(y_t/y_t^P)],\end{aligned} \tag{16}$$

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.

4. Equilibrium and Calibration

Our model's systematic equilibrium encompasses the set of difference equations representing the model's first-order conditions, the identity equations, and the exogenous energy price shock process. The 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.[23] Our system of equations is linearized around its 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 New Keynesian model with a downward rigid nominal wage inequality constraint.[24]

Table 2 displays the parameters calibrated to quarterly values. To begin, 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

---

[23] 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.

[24] Holden and Paetz (2012) develop a method to solve and simulate New Keynesian models with occasionally binding constraints. In addition to solving the model when the constraint binds, the authors' 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.

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	ν_h	–0.9
CES Capital/Energy Substitution Parameter	ν_f	–0.9
Energy's Share Used in Consumption	e_h/c	0.060
Energy's Share Used in Production	b	0.045
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

Frisch labor supply elasticity, $1/\zeta$, is fixed to Heathcote, Storesletten, and Violante's (2014) estimate of 0.72.[25] The values of a_1 and a_2 from the aggregate consumption equation, (3), are set so the ratio of energy used in consumption to aggregate consumption equals its average of 0.060 from 1972:Q1 to 2017:Q4.[26] 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 that the two goods are compliments. We assume that the price elasticity of demand, ϵ, is 6, so the steady-state markup of price over marginal cost is 20 percent. The capital depreciation rate, δ, is calibrated to 0.025, while

---

[25] Heathcote, Storesletten, and Violante (2014) estimate the Frisch labor supply elasticity to be 0.72 when a household is defined as a husband and a wife. Given that many New Keynesian models utilize higher values for the Frisch labor supply elasticity, we examine the sensitivity of our results to higher values later in the paper.

[26] The ratio of energy consumption to aggregate consumption is calculated as the average ratio of personal consumption expenditures: goods and services to personal consumption expenditures.

the investment adjustment costs parameter, κ, is set to Christiano, Eichenbaum, and Evans' (2005) estimate of 2.5.

In the production function, capital and energy's share in production, α, is set to 0.33, while b is fixed so energy's share in production equals its average of 0.045 from 1972:Q1 to 2017:Q4.[27] We follow Gavin, Keen, and Kydland (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 that 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.[28] The gross steady-state quarterly core inflation rate, π_n^*, is equal to 1.005, which is consistent with a 2 percent annual inflation rate target.[29] Finally, the AR coefficient in the energy price shock process, ρ_e, is set to 0.95 as in Wei (2003).

5. Model Results

5.1 Impulse Response Functions

Figure 6 shows the impulse response functions of key variables to a 35 percent increase in the energy price both with flexible nominal wages ($\gamma = 0$) and downward rigid nominal wages ($\gamma = 1$). A 35 percent energy price increase approximately matches the large rise in U.S. energy prices during 1974:Q4, 1990:Q3, and 1990:Q4. The impulse responses for output, investment, aggregate consumption, non-energy consumption, core inflation rate, headline inflation,

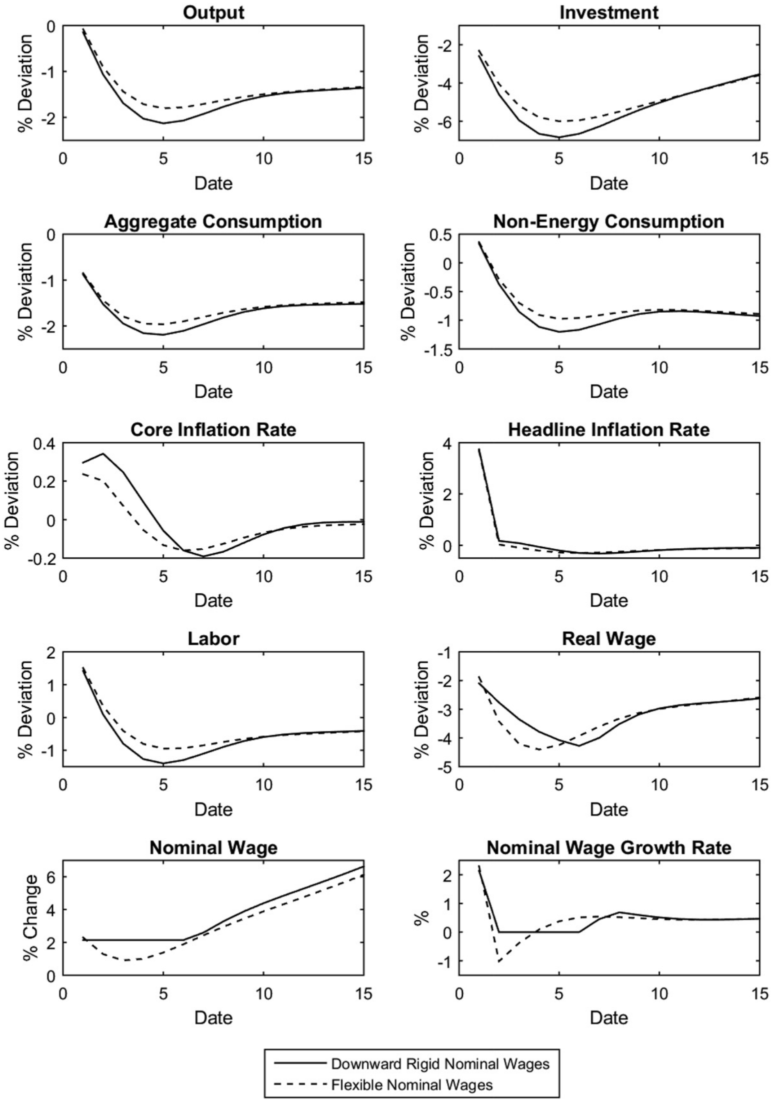
---

[27] The 2020 Annual Energy Review publishes annual data on energy's share of GDP (see Table 1.7). The annual level of energy's share of production is calculated by subtracting personal consumption expenditures: goods and services share of GDP from energy's share of GDP. Finally, our parameter is calibrated to the average level of energy's share of GDP from 1972 to 2017.

[28] Since the model is quarterly, the Taylor (1993) rule coefficient on output, θ_y, of 0.5 is divided by 4.

[29] The steady-state core inflation rate, π_n^*, equals the steady-state headline inflation rate, π^*, in our model.

Figure 6. Impulse Responses to a 35 Percent Oil Price Increase



labor, and the real wage are the percent deviations from their steady states, while the responses for the nominal wage and nominal wage growth rate are the percentage change from its initial value and the actual growth rate, respectively.[30] In a linearized model, identically sized increases and decreases in energy prices have symmetric effects. The presence of downward rigid nominal wages, however, causes the effects of an energy price increase to differ in magnitude from the effects of the same-sized energy price decline. The difference between the impulse responses in Figure 6 illustrates the approximate asymmetric effects of an energy price shock in our model with downward rigid nominal wages.

The dashed line in Figure 6 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 to raise prices. The lower supply of output puts downward pressure on real wages and capital rents 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 labor supply and decreasing their leisure.[31] The increase in labor supply combined with the decrease in labor demand pushes down the real wage, but it 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.

---

[30] In the steady state, prices rise by 0.5 percent each period. Thus, the steady-state nominal wage increases by 0.5 percent each period, which means the steady-state nominal wage growth rate is a constant 0.5 percent.

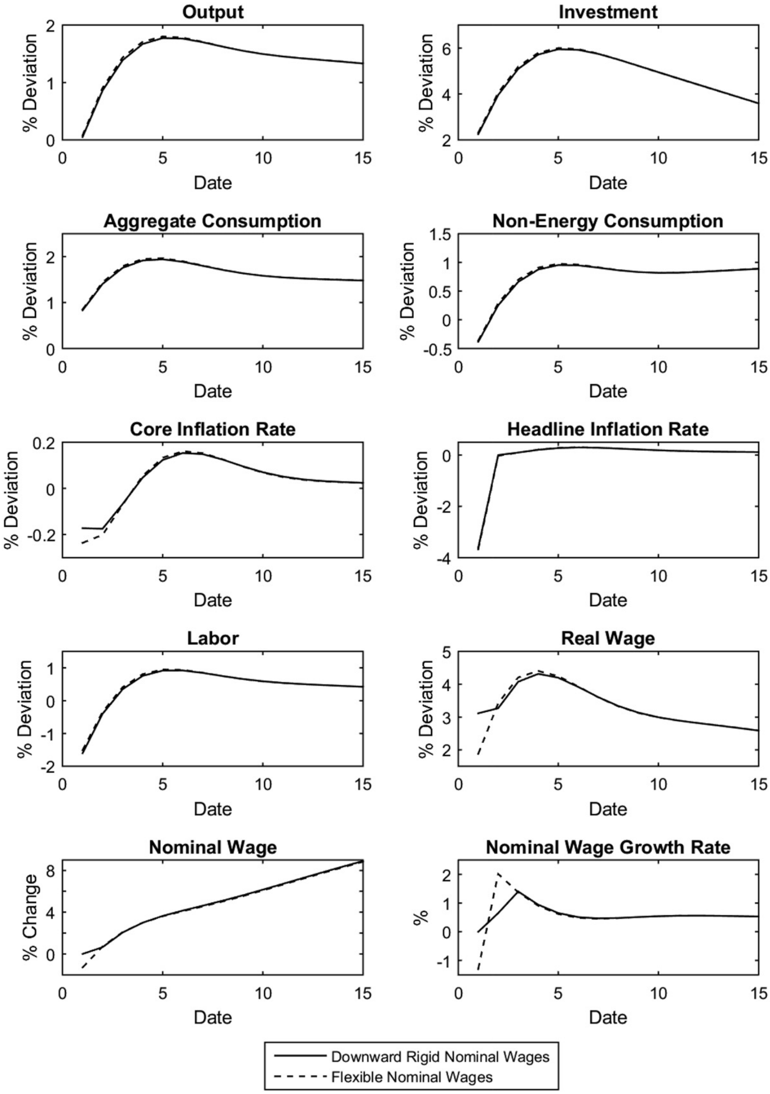
[31] Bodenstein, Guerrieri, and Gust (2013) argue that households do not increase labor supply after a negative energy shock when a Greenwood, Hercowitz, and Huffman (1988) style of utility function is used instead of the additively separable utility function employed here. One impact from labor supply 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, 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 for non-energy consumption continues to fall in the short term. The continued decline in output demand and supply causes output to fall for another four periods. Reduced 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 headline inflation, so the nominal wage growth rate turns negative. After several periods, firms start to lower their prices in response to declining energy prices, which stimulates output and pushes the economy back to its steady state.

The solid line in Figure 6 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 from declining. Firms react to those higher labor costs by reducing their output further and by raising their prices more. The price increases cause households to enhance their cuts to aggregate consumption and investment. The effects of the downward nominal wage rigidity continue to affect the economy directly, as long as the nominal wage is higher than it otherwise would have been in the absence of the downward rigidity. Even after the downward wage constraint no longer binds, 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 is binding. Thus, the downward rigid nominal wage model produces a larger and more persistent output decline than in the flexible nominal wage model.

Figure 7 displays the impulse response functions of key economic variables to a 35 percent 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 these impulse responses is

Figure 7. Impulse Responses to a 35 Percent Oil Price Decrease



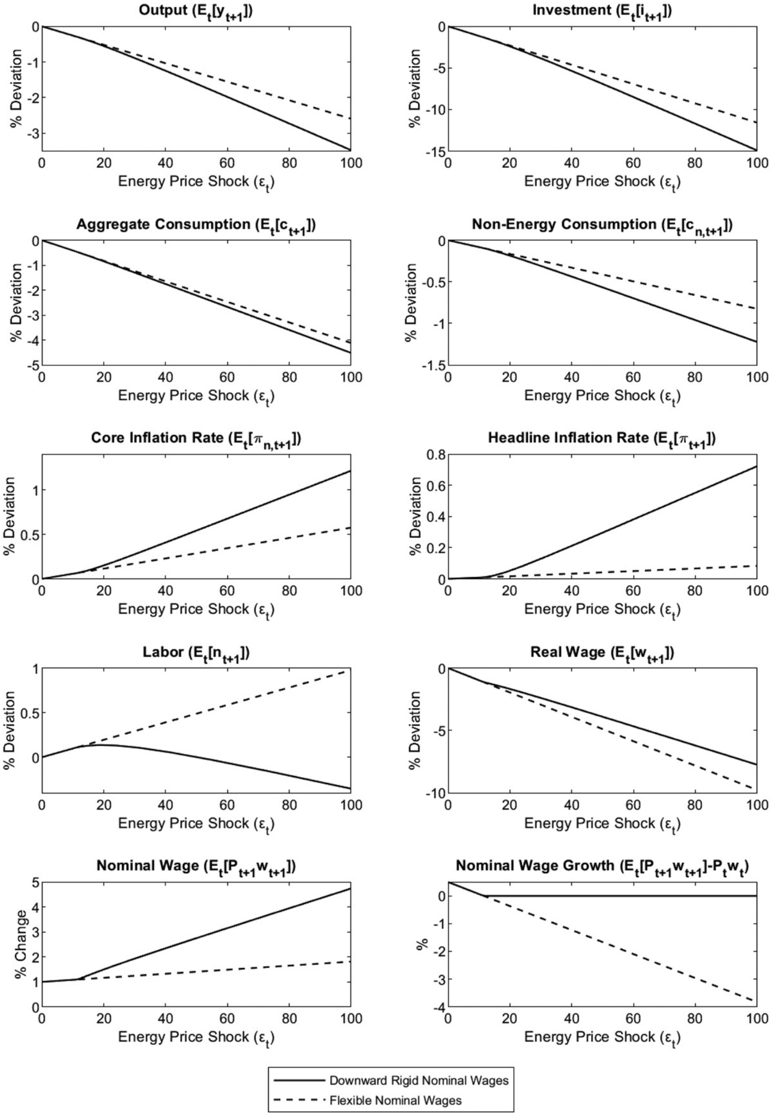
a large fall in energy prices only causes the downward rigid nominal wage constraint to bind in the initial period. The nominal wage constraint binds because lower energy prices push down the headline price level at a faster rate than firms' increased demand for labor drives up the market-clearing real 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 that a large energy price decrease generates impulse response functions for the downward rigid nominal wage 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 due primarily to the wage constraint binding after an energy price increase, as opposed to an energy price decrease. Therefore, the remainder of our analysis focuses on comparing the impact of energy price increases on our downward rigid nominal wage model and flexible nominal wage model.

5.2 Decision Rules

Figure 8 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 percent to 100 percent 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 following an energy price increase (i.e., period $t + 1$). The solid line displays the impact of an energy price increase on a model with downward rigid nominal wages, while the dashed line shows its effect on a model with flexible 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 non-linear feature into the otherwise linear flexible wage model. Thus, any deviation of the downward rigid nominal wage model's decision rules from the flexible nominal wage model's decision rules represents the asymmetric

Figure 8. Period $t + 1$ Decision Rules as a Function of the Energy Price Shock (ε_t)



and non-linear effects that are attributable to the downward rigid nominal wage constraint.

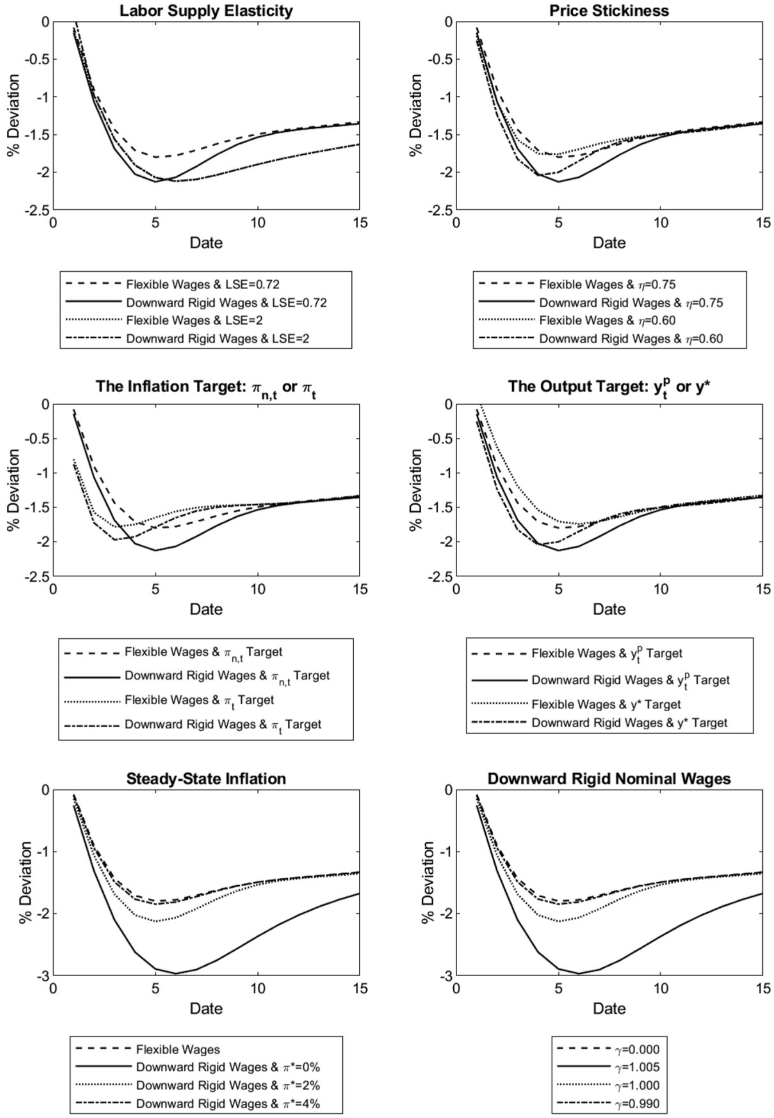
The results in Figure 8 reveal that for small energy price shocks, $\varepsilon_t \leq 11\%$, the nominal wage growth rate is positive, so both models generate identical results because the downward rigid nominal wage constraint does not bind. When $\varepsilon_t > 11\%$, the nominal wage cannot fall in the downward rigid nominal wage model, so output, aggregate consumption, non-energy consumption, and investment decline at faster rates than in the flexible wage model, while core inflation and headline inflation rise at quicker rates. The spread between the solid and dashed lines continues to grow as the size of the oil price shock rises, which indicates the responses from the downward rigid nominal wage model are rising in a non-linear manner. That result suggests a model with downward rigid nominal wages generates responses to an 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 depend, 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 monetary authority's choice of inflation and output targets, the amount of steady-state inflation, and the degree of downward rigid nominal wages. Figure 9 illustrates the impact of those features on output's response to a 35 percent increase in the energy price.

The top, left-hand graph of Figure 9 displays the impact of the labor supply elasticity on output's response to a 35 percent 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 the labor supply elasticity to 0. Our baseline model calibrates the labor supply elasticity to Heathcote, Storesletten, and Violante's (2014) estimate of 0.72. Since others, such as Christiano and Eichenbaum (1992), use a much higher labor supply elasticity, we also examine output's response

Figure 9. Output's Response to a 35 Percent Oil Price Increase: A Sensitivity Analysis



when the labor elasticity is equal to 2. The solid and dashed lines display the impulse responses for a downward rigid nominal wage model and a flexible nominal wage 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 essentually identical in the models with downward rigid nominal wages and flexible nominal wages. That is, output's asymmetric response to an energy price increase in a model with downward rigid nominal wages essentially disappears when labor supply elasticity is 2. The intuition is 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 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 the downward rigid nominal wage constraint binds.

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 9. The solid and dashed lines show the impact of a 35 percent energy price increase on output in the downward rigid nominal wage and flexible nominal wage models, respectively, when prices change on average once a year, $\eta = 0.75$. We next examine the effect of an energy price increase when prices adjust on average once every 2.5 quarters, $\eta = 0.60$. The dash-dotted line and dotted line illustrate the responses of output in the downward rigid wage model and flexible nominal wage model, respectively, when $\eta = 0.60$. Our results show that 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 of time.

The impact of the monetary authority's choice of inflation and output targets on output's response to a 35 percent energy price increase is examined in the middle graphs of Figure 9. The solid and dashed lines on the middle, left-hand graph display output's responses in the downward rigid nominal wage and flexible nominal wage models, respectively, when core inflation, $\pi_{n,t}$, is the target of monetary policy, while the dash-dotted and dotted lines show output's responses in the same models when headline inflation, π_t, is the policy target. The impulse responses for output are less asymmetric in the downward rigid nominal wage model in economies where the monetary authority targets headline inflation. When the energy price jumps, the initial increase in headline inflation is much larger than in core inflation, but in subsequent periods, headline inflation lags behind core inflation as the energy price slowly declines. That higher initial increase causes the nominal interest rate to rise more on impact when monetary policy targets headline inflation, as opposed to core inflation. The elevated nominal rate pushes down output more aggressively, which leads to a larger initial decline in the real wage. In subsequent periods, the real wage, having already experienced a large drop, does not decline as much as it does when core inflation is the policy target. That smaller decrease prevents the downward nominal wage rigidity from binding as long, and as a result, the degree of asymmetry in output's response is more modest when monetary policy targets headline inflation.

A similar but less dramatic change in output's response to a 35 percent energy price increase occurs when the monetary authority targets steady-state output, y^*, as opposed to potential output y_t^p. The solid and dashed lines on the middle, right-hand graph of Figure 9 display output's responses in the downward rigid nominal wage and flexible nominal wage models, respectively, when monetary policy targets potential output, while the dash-dotted and dotted lines show output's responses in the same models when steady-state output is the policy target. The key difference between potential output and steady-state output is that potential output falls after an energy price increase, while steady-state output remains unchanged. As a result, the output gap (actual output minus its target) decreases more when the monetary authority targets steady-state output. That larger decline in the output gap dampens the policy-induced increase in the nominal interest rate, which leads to higher headline and core inflation and a smaller drop in the real wage. The inflation and real wage responses put upward pressure on the nominal wage, which reduces the asymmetry in output's response when steady-state output rather than potential output is the policy target.

The bottom, left-hand graph of Figure 9 illustrates how the steady-state inflation rate, π^*, affects 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 always remain 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 wage model when the steady-state annual inflation rate is 0 percent, 2 percent, and 4 percent, respectively. The differences between each line and the dashed line indicate the degree of asymmetry in output's response to an energy price increase. Those results demonstrate that the degree of asymmetry is the greatest when the steady-state inflation rate is low, 0 percent, and is much more muted when the steady-state inflation rate is high, 4 percent. 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 9 shows that 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 when nominal wages must rise by at least 0.5 percent a period ($\gamma = 1.005$), cannot fall at all ($\gamma = 1.000$), and can only fall by 0.5 percent a period ($\gamma = 0.995$), 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 (i.e., 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 reveals 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 parameters. Specifically, 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 monetary authority targets core inflation and potential output, the steady-state inflation rate is low, and the degree of downward rigid nominal wages is high.

5.4 Comparing the 1970s with the 2000s

Oil price shocks produced much larger effects on output in the 1970s than in the 2000s. Compared with the 2000s, the 1970s was a period in which energy's shares of consumption and output were larger, monetary policy responded less aggressively to inflation, the steady-state inflation rate was higher, and wage indexation to inflation was more prevalent. This section examines how those factors affect output's response to an energy price shock in New Keynesian models with and without downward rigid nominal wages.

Our calibration of the 1970s' economy and the 2000s' economy will reflect the difference in energy's shares, the monetary policy rule, steady-state inflation, and the degree of downward rigid nominal wages that existed during those periods. The model of the 1970s is calibrated to data from 1973:Q1 through 1979:Q3, which coincides roughly with the period from the end of the Bretton Woods fixed exchange rate system to the beginning of the Volcker disinflation in October 1979. The model representing the 2000s is calibrated to data from 2000:Q1 through 2017:Q4. Beginning with the monetary policy rule, the parameters, θ_π, θ_y, and θ_R, from the 1970s' model are set to Mehra's (2002) estimates of 1.1, 0.1625, and 0.44, respectively, and their counterparts for the 2000s' model are set to our baseline values of 1.5, 0.125, and 0.7, respectively.[32] Energy's shares of consumption and production are set to their averages of 0.073 and 0.051, respectively, in the 1970s' model and to 0.056 and 0.040, respectively, in the 2000s' model. The average annual inflation rate was 8 percent in the 1970s, so π_n^* is set to 1.02 in the 1970s' model. During the 2000s, the Federal Reserve targeted a 2 percent inflation rate, so π_n^* is set to 1.005 in that model.[33] Holland (1988, 1995) shows that the higher inflation rates of the 1970s led to many workers, both unionized and non-unionized, receiving automatic cost-of-living increases. Those automatic raises caused the degree of the downward nominal wage rigidity, γ, to increase. Blanchard and Gali (2010) acknowledge

---

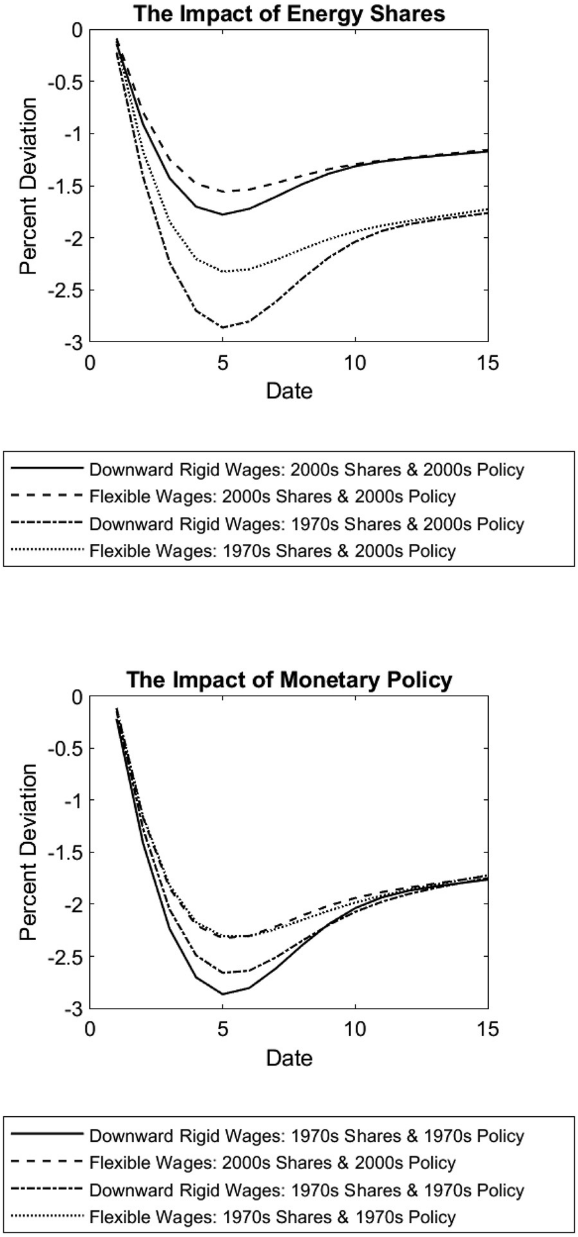
[32] Like the baseline model, the θ_y coefficients of 0.65 and 0.5 are divided by 4 because the model is quarterly.

[33] In the early 2000s, the market participants believed the Federal Reserve was targeting an inflation rate of 2 percent. That 2 percent inflation target was confirmed by the Federal Reserve on January 25, 2012.

this connection by stating, “the 1970s were times of strong unions and high wage indexing” to inflation. Since we do not have a precise estimate for γ, we calibrate the parameter to 1.015 in the 1970s’ model, but keep it equal to the baseline value of 1.000 in the 2000s’ model. Those values reflect the higher level of wage indexation in the 1970s, while maintaining the spread between π_n^* and γ in the 1970s’ model and 2000s’ model, so our analysis can focus on the impact of differences in energy’s shares and monetary policy on the two models.

Figure 10 compares the impact of an energy price shock on output in the 1970s, when energy’s shares of consumption and production were larger and monetary policy was less focused on inflation, with that of the 2000s. The top graph of Figure 10 displays the effect of the different energy’s shares on output’s response to a 35 percent energy price increase when the monetary authority follows a 2000s’ policy. The solid and dashed lines represent output’s response with energy shares from the 2000s in both the downward rigid nominal wage model and the flexible wage model, respectively, while dash-dotted and dotted lines show the same respective responses with energy shares from the 1970s. Those impulse response functions reveal that the larger energy shares in the 1970s enhance the decline in output after a 35 percent energy price increase in both models. The bottom graph of Figure 10 shows how the change in monetary policy from the 1970s to the 2000s affects output’s response after an energy price shock when energy’s shares are at 1970s’ levels. The solid and dashed lines represent output’s response with monetary policy from the 2000s in both the downward rigid nominal wage model and the flexible wage model, respectively, while dash-dotted and dotted lines show the same respective responses with monetary policy from the 1970s. The impulse responses show that the change in monetary policy has no meaningful effect on output’s response in the flexible wage model. Output’s response, however, is more muted in the downward rigid wage model with 1970s’ monetary policy than with 2000s’ monetary policy. The larger emphasis on output stability and the smaller emphasis on inflation stability in the 1970s’ monetary policy caused the real wage to fall less and inflation to rise more, which put upward pressure on the nominal wage after an energy price increase. Therefore, our downward rigid nominal wage model attributes the larger output decline after an energy price increase in the

Figure 10. Output's Response to a 35 Percent Oil Price Increase: A Comparison of the 1970s with the 2000s



1970s to that period's higher level of energy's shares of consumption and production and not to that period's monetary policy.[34]

5.5 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 that 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. Recall from the discussion of Figure 1 that the large oil price increases of 1973–74, 1979–80, 1981, and 1990 are usually attributed to foreign oil supply disruptions, while the 2002–08 oil price spike is often attributed to the large rise in oil demand from China and India.

One drawback of our model is that it does not distinguish between energy price shocks caused by changes in foreign energy demand and supply. We can use an open-economy New Keynesian model by Balke and Brown (2018), however, to infer how energy price shocks caused by changes in foreign energy demand and supply affect our model. Specifically, the authors examine separately the impact of a rise in energy prices caused by an increase in foreign demand or a decrease in foreign supply. They find that an increase in foreign energy demand generates a larger rise in domestic prices and a smaller decline in domestic output than a comparable fall in foreign energy supply. Balke and Brown's rationale is straightforward in that an increase in foreign energy demand is usually 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 fall in domestic output caused by higher energy prices and put more upward pressure on domestic prices.

---

[34] Empirical studies have produced conflicting results on whether U.S. monetary policy enhanced output's response to oil price shocks in the 1970s. See Bernanke, Gertler, and Watson (1997), Hamilton and Herrera (2004), and Kilian and Lewis (2011).

In contrast, a decrease in foreign energy supply pushes down output worldwide, which reduces international trade. If the decreases in domestic exports and domestic imports are offsetting, then an energy price increase caused by a decline in foreign energy supply has no additional effects on our model.[35]

The findings of Balke and Brown (2018) suggest our model is best at explaining the effects of an energy price increase caused by a decline in foreign energy supply. The authors' results, however, have implications for how our model's results would change when an energy price increase is caused by an increase in 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 early periods, while the larger rise in the price level implies the inflation rate initially will be higher. That combination of responses signifies the economy is less likely to hit the downward nominal wage constraint. Therefore, an energy price shock caused by a foreign supply disruption will have a larger asymmetric effect on output 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 real wage rate's decline, which forces firms to reduce output more than without the constraint. That downward constraint, however, has no meaningful impact on the real wage after an energy price decrease, so

---

[35] Another possibility is that an oil price increase is caused by an increase in domestic demand. For example, suppose a positive domestic or worldwide aggregate demand shock raises the demand for energy, which leads to a jump in the energy price. That higher price would raise the real marginal cost leading to a smaller increase in output and a larger rise in inflation.

output does not rise as aggressively. Thus, downward rigid nominal wages cause energy price shocks to have asymmetric effects on the macroeconomy. Our results show the degree of asymmetry 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 asymmetric response to oil price shocks. 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 percent 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. As such, those firms were forced to reduce their output further. The example shows that a downward rigid nominal wage constraint is a reasonable mechanism to include in any theoretical model seeking to explain output's asymmetric response to a large oil price shock.

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 below 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. That 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 necessary when addressing questions, such as the optimal policy response to oil price shocks, where precise quantitative results matter. Those topics, however, are beyond the scope of this paper and are left for future research.

References

Aastveit, K. 2014. "Oil Price Shocks in a Data-Rich Environment." *Energy Economics* 45 (September): 268–79.

Abbritti, M., and S. Fahr. 2013. "Downward Wage Rigidity and Business Cycle Asymmetries." *Journal of Monetary Economics* 60 (7): 871–86.

Abo-Zaid, S. 2013. "Optimal Monetary Policy and Downward Nominal Wage Rigidity in Frictional Labor Markets." *Journal of Economic Dynamics and Control* 37 (1): 345–64.

Balke, N. S., and S. P.A. Brown. 2018. "Oil Supply Shocks and the U.S. Economy: An Estimated DSGE Model." *Energy Policy* 116 (May): 357–72.

Baqaee, D. R. 2020. "Asymmetric Inflation Expectations, Downward Rigidity of Wages, and Asymmetric Business Cycles." *Journal of Monetary Economics* 114 (October): 174–93.

Barattieri, A., S. Basu, and P. Gottschalk. 2014. "Some Evidence on the Importance of Sticky Wages." *American Economic Journal: Macroeconomics* 6 (1): 70–101.

Benigno, P., and L. A. Ricci. 2011. "The Inflation-Output Trade-Off with Downward Wage Rigidities." *American Economic Review* 101 (4): 1436–66.

Bernanke, B. S. 1983. "Irreversibility, Uncertainty, and Cyclical Investments." *Quarterly Journal of Economics* 97 (1): 85–106.

Bernanke, B. S., M. Gertler, and M. W. Watson. 1997. "Systematic Monetary Policy and the Effects of Oil Price Shocks." *Brookings Papers on Economic Activity* 1: 91–157.

Blanchard, O., and J. Gali. 2010. "The Macroeconomic Effects of Oil Price Shocks: Why are the 2000s so Different from the 1970s?" In *International Dimensions of Monetary Policy,* ed. J. Gali and M. Gertler, 373–428. Chicago: University of Chicago Press.

Blanchard, O., and M. Riggi. 2013. "Why Are the 2000s so Different from the 1970s? A Structural Interpretation of Changes in the Macroeconomic Effects of Oil Prices." *Journal of the European Economic Association* 11 (5): 1032–52.

Bodenstein, M., C. J. Erceg, and L. Guerrieri. 2008. "Optimal Monetary Policy with Distinct Core and Headline Inflation Rates." *Journal of Monetary Economics* 55 (Supplement): S18–S33.

Bodenstein, M., L. Guerrieri, and C. J. Gust. 2013. "Oil Shocks and the Zero Bound on Nominal Interest Rates." *Journal of International Money and Finance* 32 (February): 941–67.

Calvo, G. A. 1983. "Staggered Prices in a Utility Maximizing Framework." *Journal of Monetary Economics* 12 (3): 383–98.

Christiano, L. J., and M. Eichenbaum. 1992. "Current Real-Business Cycle Theories and Aggregate Labor-Market Fluctuations." *American Economic Review* 82 (3): 430–50.

Christiano, L. J., M. Eichenbaum, and C. L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy* 113 (1): 1–45.

Daly, M. C., and B. Hobijn. 2014. "Downward Nominal Wage Rigidities Bend the Phillips Curve." *Journal of Money, Credit and Banking* 46 (S2): 51–93.

Dhawan, R., and K. Jeske. 2008. "Energy Price Shocks and the Macroeconomy: The Role of Consumer Durables." *Journal of Money, Credit and Banking* 40 (7): 1357–77.

Dhawan, R., K. Jeske, and P. Silos. 2010. "Productivity, Energy Prices, and the Great Moderation: A New Link." *Review of Economic Dynamics* 13 (3): 715–24.

Dixit, A., and J. Stiglitz. 1977. "Monopolistic Competition and Optimum Product Diversity." *American Economic Review* 67 (3): 297–308.

Drechsel, T., and S. Tenreyro. 2018. "Commodity Booms and Busts in Emerging Economies." *Journal of International Economics* 112 (1): 200–218.

Gavin, W. T., B. D. Keen, and F. T. Kydland. 2015. "Monetary Policy, the Tax Code, and the Real Effects of Energy Shocks." *Review of Economic Dynamics* 18 (3): 694–707.

Gottschalk, P. 2005. "Downward Nominal-Wage Flexibility: Real or Measurement Error?" *Review of Economics and Statistics* 87 (3): 556–68.

Greenwood, J., Z. Hercowitz, and G. W. Huffman. 1988. "Investment, Capacity Utilization, and the Real Business Cycle." *American Economic Review* 78 (3): 402–17.

Hamilton, J. D. 1988. "A Neoclassical Model of Unemployment and the Business Cycle." *Journal of Political Economy* 96 (3): 593–617.

———. 1996. "This Is What Happened to the Oil Price/Macroeconomy Relation." *Journal of Monetary Economics* 38 (2): 215–20.

———. 2003. "What is an Oil Price Shock?" *Journal of Econometrics* 113 (2): 363–98.

———. 2008. "Oil and the Macroeconomy." *New Palgrave Dictionary of Economics,* ed. S. Durlauf and L. Blume. Palgrave Macmillan.

———. 2011. “Nonlinearities and the Macroeconomic Effects of Oil Prices.” *Macroeconomic Dynamics* 15 (S3): 364–78.

Hamilton, J. D., and A. M. Herrera. 2004. “Oil Shocks and Aggregate Economic Behavior: The Role of Monetary Policy.” *Journal of Money, Credit and Banking* 36 (2): 265–86.

Hazell, J., and B. Taska. 2018. “Posted Wage Rigidity.” Manuscript.

Heathcote, J., K. Storesletten, and G. L. Violante. 2014. “Consumption and Labor Supply with Partial Insurance: An Analytical Framework.” *American Economic Review* 104 (7): 2075–2126.

Herrera, A. M., L. Lagalo, and T. Wada. 2011. “Oil Price Shocks and Industrial Production: Is the Relationship Linear?” *Macroeconomic Dynamics* 15 (S3): 472–97.

Holden, T., and M. Paetz. 2012. “Efficient Simulation of DSGE Models with Inequality Constraints.” Manuscript.

Holland, A. S. 1988. “The Changing Responsiveness of Wages to Price-Level Shocks: Explicit and Implicit Indexation.” *Economic Inquiry* 26 (2): 265–79.

———. 1995. “Inflation and Wage Indexation in the Postwar United States.” *Review of Economics and Statistics* 77 (1): 172–76.

Jo, Y. J. 2021. “Establishing Downward Nominal Wage Rigidity Through Cyclical Changes in the Wage Distribution.” Manuscript.

Jorda, O. 2005. “Estimation and Inference of Impulse Responses by Local Projections.” *American Economic Review* 95 (1): 161–82.

Keen, B. D., and E. F. Koenig. 2018. “How Robust Are Popular Models of Nominal Frictions?” *Journal of Money, Credit and Banking* 50 (6): 1299–1342.

Kilian, L. 2008. “The Economic Effects of Energy Price Shocks.” *Journal of Economic Literature* 46 (4): 871–909.

———. 2009. “Not All Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market.” *American Economic Review* 99 (3): 1053–69.

Kilian, L., and L. Lewis. 2011. “Does the Fed Respond to Oil Price Shocks?” *Economic Journal* 121 (555): 1047–72.

Kilian, L., and C. Vega. 2011. “Do Energy Prices Respond to U.S. Macroeconomic News? A Test of the Hypothesis of Predetermined Energy Prices.” *Review of Economics and Statistics* 93 (2): 660–71.

Kilian, L., and R. J. Vigfusson. 2011. “Are the Responses of the U.S. Economy Asymmetric in Energy Price Increases and Decreases?” *Quantitative Economics* 2 (3): 419–53.

———. 2013. “Do Oil Prices Help Forecast U.S. Real GDP? The Role of Nonlinearities and Asymmetrics.” *Journal of Business and Economic Statistics* 31 (1): 78–93.

Kim, J., and F. J. Ruge-Murcia. 2009. “How Much Inflation Is Necessary to Grease the Wheels?” *Journal of Monetary Economics* 56 (3): 365–77.

———. 2011. “Monetary Policy When Wages Are Downwardly Rigid: Friedman Meets Tobin.” *Journal of Economic Dynamics and Control* 35 (12): 2064–77.

Mehra, Y. P. 2002. “The Taylor Principle, Interest Rate Smoothing and Fed Policy in the 1970s and 1980s.” Working Paper No. 02-03, Federal Reserve Bank of Richmond.

Mork, K. 1989. “Oil and the Macroeconomy When Prices Go Up and Down: An Extension of Hamilton’s Results.” *Journal of Political Economy* 91 (3): 740–44.

Plante, M. 2014. “How Should Monetary Policy Respond to Changes in the Relative Price of Oil? Considering Supply and Demand Shocks.” *Journal of Economic Dynamics and Control* 44 (July): 1–19.

Ramey, V. A., and S. Zubairy. 2018. “Government Spending Multipliers in Good Times and in Bad: Evidence from US Historical Data.” *Journal of Political Economy* 126 (2): 850–901.

Schmitt-Grohe, S., and M. Uribe. 2016. “Downward Nominal Wage Rigidity, Currency Pegs, and Involuntary Unemployment.” *Journal of Political Economy* 124 (5): 1466–1514.

Sims, C. 2002. “Solving Linear Rational Expectations Models.” *Computational Economics* 20 (1–2): 1–20.

Taylor, J. B. 1993. “Discretion Versus Policy Rules in Practice.” *Carnegie-Rochester Conference Series on Public Policy* 39 (1): 195–214.

Wei, C. 2003. “Energy, the Stock Market, and the Putty-Clay-Investment Model.” *American Economic Review* 93 (1): 311–23.