ARGUMENTA OECONOMICA
No 2 (41) 2018
PL ISSN 1233-5835

I. ARTICLES

Farhad Taghizadeh-Hesary, Naoyuki Yoshino***

ASSESSMENT OF THE CHANNELS OF TRANSMISSION OF OIL PRICE FLUCTUATIONS TO THE ECONOMY

This paper develops a New Keynesian model to examine a theoretical global economy with two basic macroeconomic components: an energy[1] producer and an energy consumer. This simple economy uses these two components to evaluate how oil prices affect the consumer economy's gross domestic product and inflation. This model assumes that changes in the oil price transfer to macro variables through either supply (aggregate supply curve) or demand channels (aggregate demand curve). To examine the effects of this transfer, an Investment-Saving (IS) curve is used to look at the demand side and a Phillips curve is used to analyze the inflationary effects from the supply side. The empirical analysis concludes that movements in the oil price mainly affect the economy through the demand side (shifting the aggregate demand curve) by affecting household expenditures and energy consumption. This analysis provides several additional findings, among which is that easy monetary policies amplify energy demand more than supply, resulting in skyrocketing crude oil prices, which inhibit economic growth.

Keywords: oil prices, New Keynesian model, IS curve, Phillips curve, monetary policy
JEL Classifications: Q41, Q43, E12, E52
DOI: 10.15611/aoe.2018.2.01

1. INTRODUCTION

The sharp increase in oil prices that began in 2001, the sharp decline that followed in 2008, and most recently the sharp decline starting from September 2014, have renewed interest in the effects brought by oil prices on the macroeconomy. The price of oil more than halved in less than five months since September 2014. After nearly five years of stability, the price of a barrel of Brent crude oil in Europe fell from over $100 in September 2014, to less than $46 in January 2015. A lot of research has been done on the effects oil prices have on the macroeconomy, and the findings

* Faculty of Political Science and Economics, Waseda University, Tokyo, Japan.
** Asian Development Bank Institute (ADBI); Keio University, Tokyo, Japan.
[1] From now on in this paper whenever we refer to "energy" or "energy prices", we refer to "crude oil" and "crude oil price", which is the main source of energy.

consistently indicate that rising oil prices have a large adverse impact on the rate of gross domestic product (GDP) growth. Bohi (1991), for example, examined the oil shocks in the 1970s by analyzing disaggregated industry data for Japan, the United States (US), the United Kingdom (UK), and Germany, and found that each price shock sparked a decline in GDP. Hamilton (1983) turned his attention to the US economic recession that followed these oil shocks and hypothesized that this recession was due in large part to elevated oil prices. He came to this conclusion by using the Granger-causality model along with six other variables that can reduce the real US GDP. Alterman (1985) brought a higher level of specificity to his analysis, stating that higher energy prices could have accounted for a decline in the growth of the US gross national product (GNP) by as much as 0.72% in 1974 and 0.36 % in 1979–1980. To give a basis for comparison, actual GNP growth went from 4.5% in 1972–1973 to –0.8% during 1974–1975, and from 4.7% during 1976–1978 to 0.9% during 1979–1980. Javier (1993) found the absolute value of the price elasticity of GNP on the price of oil to be 0.055%. Cunado and Perez de Gracia (2003) studied a sample of several European economies and found that oil prices have a significant impact on growth in Europe as well. Taghizadeh-Hesary et al. (2013) evaluated the impact of oil price shocks on oil producing and consuming economies, examining their trade patterns during 1991Q1–2011Q4. They found that among oil producers in their survey, Iran and the Russian Federation benefit from oil price shocks but Canada seems to suffer, while for oil-consuming economies, the effects are more diverse, with some benefitting and others worse off. In a recent study, Taghizadeh-Hesary et al. (2016) assessed the impact of crude oil price movements on two macro variables, GDP growth rate and consumer price index inflation rate, in the developed economies of the United States and Japan, and an emerging economy, the People's Republic of China (PRC). Their results suggest that the impact of oil price fluctuations on developed oil importers' GDP growth is much lower than on the GDP growth of an emerging economy. On the other hand, the impact of oil price movements on the PRC's inflation rate was found to be milder than in the two developed countries that were examined.

These papers have mainly empirical approaches to their research, however, a theoretical analysis in this field is scarce. In addition to the lack of theoretical foundation behind the analyses contained in these papers, they often contradict each other when it comes to the issue of whether the supply of the economy (aggregate supply) or the demand side of the economy (aggregate demand) is affected more by increases in the oil price. Research in the early 1980s tended to indicate that the supply side of the economy was more heavily impacted by changes in the oil price, but recent research often states that the demand side of the economy takes more of the brunt. This includes Bernanke (2006), who states that the demand channel is the more affected of the two because of decreases in consumer spending. In this paper we use a solid theoretical base followed by empirical analysis to determine which side of the economy is more greatly affected by oil price movements: supply or demand.

Table 1

Principal causes of major crude oil price fluctuations (1947–2014)

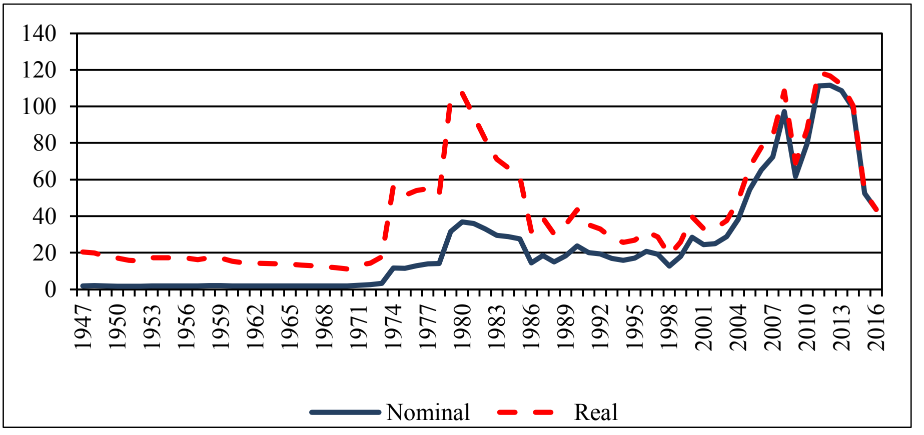
Oil price episode	Principal factors
1947–1948	Previous investment in production and transportation capacity inadequate to meet postwar needs, decreased coal production resulting from shorter work week, European reconstruction
1952–1953	Iranian oil nationalization; strikes by oil, coal, and steel workers; import stance of the Texas Railroad Commission
1956–1957	Suez crisis
1969	Secular decline in US reserves, strikes by oil workers
1970	Rupture of trans-Arabian pipeline, Libyan production cutbacks, coal price increases (strikes by coal workers, increased coal exports, environmental legislation)
1973–1974	Stagnating US production, OPEC embargo
1978–1979	Islamic revolution of Iran
1980–1981	Iran–Iraq war, removal of US price controls
1990	Iraqi invasion of Kuwait and the Persian Gulf War
1998–2000	Asian financial crisis, oil consumption decline in Asia and the Pacific
2008	Lehman shock, Global financial crisis; global decline in oil consumption
2011	Arab Spring (Start date December 18, 2010); oil supply shock
2014	Shale revolution (excess oil supply); depressed demand for oil; reasons of monetary policy

Notes: OPEC = Organization of the Petroleum Exporting Countries, US = United States.

Sources: Hamilton (1983), Taghizadeh-Hesary et al. (2013), Yoshino and Taghizadeh-Hesary (2016).

Figure 1 illustrates crude oil price movements in nominal and real terms from 1947 to 2016. The causes for major price movements become clear when comparing Figure 1 with Table 1.

As Table 1 shows, one of the reasons behind the most recent decline in the oil prices starting from end of 2014 was monetary policy. Yoshino and Taghizadeh-Hesary (2016) explain that following the subprime mortgage



Notes: Prices are in US dollars per barrel. Real prices are deflated using the Consumer Price Index for the US (2016), 1945-1983 Arabian Light posted at Ras Tanura, 1984-2016 Brent dated.

Figure 1. Crude oil prices, 1947-2016

Source: BP (2017).

crisis when the world economy was in recession, through the easy monetary policy of the United States (US) and some other developed economies following the crisis, in early 2008 and early 2009 a large amount of liquidity entered into the oil market since the developed economies were in recession so they needed a safe place in which to invest and the commodities market including oil was safe with lower fluctuations. In 2014 and 2015, following the recovery of the US economy and especially its capital market, liquidities that had moved from the disordered developed economies' capital markets to the oil and commodities markets during the global financial crisis in order to keep their real values, were coming back to the capital markets, thus reducing the global oil demand sharply and pushing the oil prices down.

We ran this research to achieve three purposes: (i) to determine the channels of transmission of higher oil prices to the macroeconomy, (ii) to develop a theoretical framework that could explain the role of oil prices in both the demand and supply sides of the economy while contributing towards asserting our empirical yields, and (iii) to clarify the role of monetary policy impacts on the demand and supply sides of the oil market. For these purposes we developed a new Keynesian model for an open economy with a microeconomic foundation for two economies: (i) energy consumers and (ii) energy producers. We used this model to evaluate how oil prices affect the macroeconomic variables of output and inflation during 1960–2011.

For the first purpose, to determine the channels of transmission of higher oil prices to the macroeconomy, we assume that in the New Keynesian model that we developed, oil price changes can be transmitted through two channels to macroeconomic variables. Our model allows oil prices to have temporary and persistent effects on output through the supply and the demand sides of the economy. Phrased more specifically, we allow oil prices to shift the Investment-Saving (IS) curve to proxy for temporary demand-side effects and to affect the Phillips curve to capture inflationary effects through the supply side.

This paper is structured as follows. In Section 2, we present the theoretical framework which describes theoretical considerations. Next, we present the three parts of our model: households, firms, and energy producers. The last part of Section 2 discusses monetary policies and crude oil prices. Section 3 describes our empirical analysis which includes data and empirical results. Section 4 concludes.

2. THEORETICAL FRAMEWORK

2.1. Theoretical considerations

As stated earlier, there are two channels for the transmission of crude oil price movements to the economy. We refer to these two channels as Case 1 and Case 2. In Case 1, the aggregate supply channel is the main transmission channel of oil price movements and in Case 2 the aggregate demand channel is the main transmission channel of oil price movements to the economy.

Case 1. Oil shocks mainly affect the supply side of the economy (aggregate supply is the main transmission channel of oil shocks).

A simple aggregate supply and demand model will clarify the analysis of this section.

In Figure 2, the economy initially is in equilibrium with price level, P_0 and real output level, Y_0, at point *A*. *AD* is the aggregate demand curve and *AS* stands for the aggregate supply curve. The aggregate supply curve is constructed with an increasing slope to show that at some real output level, it becomes difficult to increase real output despite increases in the general level of prices. At this output level, the economy achieves full employment (Tatom 1981). Suppose that the initial equilibrium, point *A* is below the full employment level.

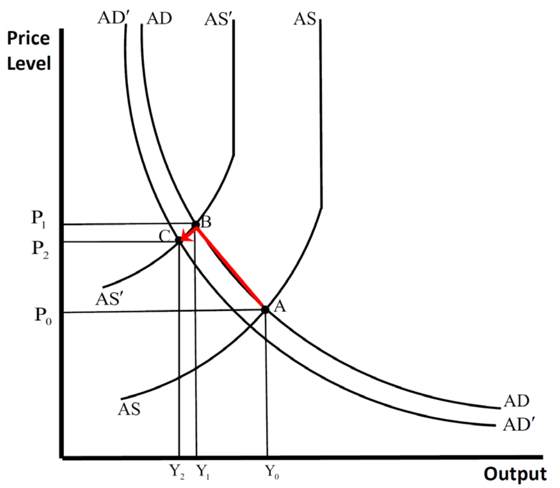


Figure 2. The effect of the higher relative price of crude oil (energy price) on output and price level

(Case 1: Supply side of the economy is more affected by oil shocks compared to demand side)

Source: compiled by authors.

When the relative price of energy resources (crude oil, natural gas, coal, among others) increases, the aggregate supply curve shifts to AS'. The employment of existing labor and capital with a given nominal wage rate requires a higher general price for output if sufficient amounts of the higher-cost energy resources are to be used.

The *productivity* of existing capital and labor resources is reduced so that potential real output declines to Y_1. In addition, the same rate of labor employment occurs only if real wages decline sufficiently to match the decline in productivity. This, in turn, happens only if the general level of prices rises sufficiently (P_1), given the nominal wage rate. This moves the economy to the level of output (Y_1) and price level (P_1). This point is indicated in Figure 2 at point B which is a disequilibrium point. Given the same supply of labor services and existing plant and equipment, the output associated with full employment declines as producers reduce their use of relatively more expensive energy resources and as plant and equipment become economically obsolete.

On the other hand, in the demand side of the economy, when the prices of energy resources rise, their consumption declines. Because of this drop in consumption, the aggregate demand curve shifts to AD', which then reduces the prices from the previous disequilibrium level at P_1 and sets them to P_2 as the final equilibrium price. This lowers the output levels due to less consumption in the economy, from the previous point of Y_1 to Y_2. This point is indicated in Figure 2 at point *C* which is the final equilibrium point.

This is an issue that Tatom (1981) did not mention in his paper, as he only examined *AS* movements in his analysis and not AD movements.

The economy may not adjust instantaneously to point *C*, even if point *C* is the new equilibrium. For example, price rigidities due to slow-moving information or other transaction costs can keep nominal prices from adjusting quickly (Tatom 1981). Consequently, output and prices move along an adjustment path such as that indicated by the arrow in Figure 2.

In Case 1, aggregate supply is the main chain of transmission of energy price shocks compared to aggregate demand. This means that the supply side of the economy is more affected by oil price shocks than the demand side of the economy, resulting in higher prices and lower output levels at the final equilibrium point (*C*) when compared to the initial equilibrium point (*A*).

Case 2. Oil shocks mainly transmit through the demand side of the economy (aggregate demand is the main transmission channel of oil shocks)

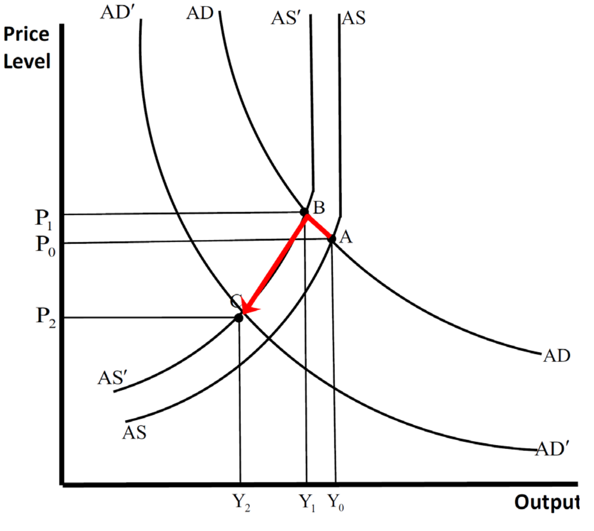


Figure 3. The effect of the higher relative price of crude oil (energy price) on output and price level

(Case 2: demand side of the economy is mainly affected by oil shocks compared to supply side)

Source: compiled by authors.

As in Case 1, also in this case, the economy initially is in equilibrium with price level P_0, and real output level Y_0. Initial equilibrium point is indicated in Figure 3 at point A. When the relative price of energy resources increases, the aggregate supply curve shifts to AS'. The employment of existing labor and capital with a given nominal wage rate requires a higher general price for output, if sufficient amounts of the higher-cost energy resources are to be used. The productivity of existing capital and labor resources is reduced so that potential real output declines to Y_1. In addition, the same rate of labor employment occurs only if real wages decline sufficiently to match the decline in productivity. This happens only if the general level of prices rises sufficiently (P_1), given the nominal wage rate, and moves the economy to the level of output (Y_1) and price level (P_1), indicated in Figure 3 at point B, which is a disequilibrium point. On the demand side of economy, higher energy prices (crude oil, natural gas, coal, among others) force consumption to decline, which reduces the total consumption of the economy, resulting in a shift of the aggregate demand curve to AD'. This shift reduces prices from the previous level of P_1 and sets them to P_2 as the final equilibrium price, while also lowering output levels because of lower consumption in the economy. Output moves from the previous point Y_1 to the new point Y_2, showing that the final equilibrium point is C.

In Case 2, aggregate demand is the main chain of transmission of energy price shocks. As can be seen in Figure 3, the shift in the aggregate demand curve is larger than the one in the aggregate supply curve, resulting in lower prices and lower output levels in the final equilibrium point (C) than the initial equilibrium point (A).

2.2. Basic model

We provide a model in the New Keynesian framework following Yoshino et al. (2012), in which we assume that there are two economies in the world: an energy consumer (in this paper, the US[2]) and an energy producer. In the energy consumer economy, there are two sectors: households and firms. Both sectors import energy from the energy producing economy (as in Taghizadeh-Hesary and Yoshino 2013).

[2] In 2010 the US consumed over 19 million barrels per day, which was more than 20% of global consumption. Despite the growth in crude oil consumption in the People's Republic of China, the Russian Federation, Latin America and the Middle East, the US remains by far the largest user of oil. In our research, since we have to use one country as the consumer of crude oil, the US is the best choice because of its high oil consumption.

Households

Let C_t be the following index of consumption of non-energy commodities (C_t^{NG}) and energy goods (C_t^{G}):[3]

$$C_t = \left(C_t^{NG}\right)^{A}\left(C_t^{G}\right)^{1-A}; \quad A<1, \tag{1}$$

Where A is the elasticity of substitution between two groups of commodities. We then can write the consumption price index (CPI) as follows:[4]

$$P_t^C = \left(\frac{A}{P_t^{NG}}\right)^{-A}\left(\frac{1-A}{P_t^{G}}\right)^{A-1} \tag{2}$$

where P_t^C denotes consumer price index (CPI) and P_t^{NG} and P_t^{G} are the prices of non-energy commodities, and energy, respectively.

The utility of a representative household is a function of: $U_t = f\left(\overset{+}{C_t}, \overset{-}{L_t}, \overset{+}{M_t}\right)$, so the utility function of a representative household can be expressed by the following:

$$U_t = E_t \sum_{t=0}^{\infty} \beta^{t}\left[\frac{1}{1-\eta}\left(C_t\right)^{1-\eta} - \frac{1}{1+\kappa}\left(L_t\right)^{1+\kappa} + \frac{\chi}{1-\sigma}\left(M_t\right)^{1-\sigma}\right] \tag{3}$$

Inside the brackets, the first term captures the instantaneous utility from consumption (both energy and non-energy commodities), the second term expresses disutility from the labor effort, and the last term defines the instantaneous utility from money holdings, where M_t denotes the representative household's real money holding, L_t is the labor supply by the

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[3] By cost minimization of the representative household, we obtain the following demand condition. As in Dixit and Stiglitz (1977), Clarida et al. (2002), and Yoshino et al. (2012), the purchase of each good satisfies the following:

$$C_t^{NG} = AC_t\left(\frac{P_t^{NG}}{P_t^{C}}\right)^{-1}, \tag{1}$$

$$C_t^{G} = (1-A)C_t\left(\frac{P_t^{G}}{P_t^{C}}\right)^{-1}. \tag{2}$$

[4] Substituting (1) and (2) of footnote 3 into Eq. (1) of the main text, the consumption price index (CPI) yields:

$$P_t^C = \left(\frac{A}{P_t^{NG}}\right)^{-A}\left(\frac{1-A}{P_t^{G}}\right)^{A-1}. \tag{1}$$

representative household, and β^t is the discount factor. The household's budget constraint in real terms is:

$$C_t = \frac{W_t}{P_t^C} L_t - \frac{M_t - M_{t-1}}{P_t^C}, \tag{4}$$

where W_t denotes the household's nominal wage per hour working. The representative household maximizes (3) subject to (4). The Euler equation[5], money demand, and the labor supply equations are derived from first-order conditions with respect to consumption in t and t+1, money holdings, and labor.

$$\frac{(C_t)^{-\eta}}{P_t^C} = \beta E_t \left[\frac{(C_{t+1})^{-\eta}}{P_{t+1}^C} \right], \tag{5}$$

$$(M_t)^{-\sigma} = \frac{(C_t)^{-\eta}}{P_t^C \chi}, \tag{6}$$

$$\frac{W_t}{P_t^C} = \frac{(L_t)^k}{(C_t)^{-\eta}}. \tag{7}$$

Formulas (5)–(7) show the Euler equation, money demand, and labor supply equations, respectively (see section (a) in the Appendix for log-linearized versions).

The demand of representative household for energy is as follows (see section (b) in the Appendix for mathematical works):

$$C_t^G = \left(\frac{1-A}{A} \right)^A \frac{\alpha_0 (E_t M_{t+1})^{\frac{\sigma}{\eta}} (W_t)^{\frac{1}{\eta}}}{(P_t^{NG})^{\frac{A(1-\eta)}{\eta}} (P_t^G)^{\frac{1-A(1-\eta)}{\eta}} (L_t)^{\frac{\kappa}{\eta}} (M_t)^{\frac{\sigma}{\eta}}}, \tag{8}$$

where $Log\alpha_0 = \dfrac{-b - \varepsilon - (A-1)z + Aa}{\eta} > 0$.

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[5] Euler equation:

$$\frac{(C_t)^{-\eta}}{P_t^C} = \beta E_t \left[\frac{(C_{t+1})^{-\eta}}{P_{t+1}^C} (1+i_t) \right], \tag{1}$$

where i is the interest rate or nominal yields of bonds in time t, but since the representative household's utility is indifferent with bonds and their yields, here our Euler equation is different from the one above.

Let us consider the following monetary equation:

$$E_t M_{t+1} = \Omega\left(E_t \pi_{t+1} - E_{t-1}\pi_t\right), \tag{9}$$

where $E_t \pi_{t+1}$ and $E_t M_{t+1}$ are the expected values of the inflation rate and money supply of the next period, respectively. We rewrite the representative household demand for energy as follows:

$$C_t^G = \left(\frac{1-A}{A}\right)^A \frac{\alpha_0 \left[\Omega\left(E_t \pi_{t+1} - E_{t-1}\pi_t\right)\right]^{\frac{\sigma}{\eta}} \left(W_t\right)^{\frac{1}{\eta}}}{\left(P_t^{NG}\right)^{\frac{A(1-\eta)}{\eta}} \left(P_t^G\right)^{\frac{1-A(1-\eta)}{\eta}} \left(L_t\right)^{\frac{\kappa}{\eta}} \left(M_t\right)^{\frac{\sigma}{\eta}}}. \tag{10}$$

Firms

Here we have a representative firm whose production depends on the employment of labor, energy input and capital. This firm's production function may be written as:

$$Q_t = A_t L_t^{\varphi} G_t^{\varpi} \bar{K}, \tag{11}$$

where Q_t is output, L_t is labor measured in man-hours, G_t is the flow of energy in barrels of crude oil, $\bar{K}$ is capital in dollars, which is a fixed amount, and t is time. A_t is a time-varying exogenous total factor productivity, and ϕ, ϖ are the output elasticities of labor and energy inputs, respectively. As in Woodford (2003), we may think of capital as being allocated to each firm in a fixed amount, with capital goods never depreciating, never being produced, and (because they are specific to the firm that uses them) never being reallocated among firms; in this case, the additional argument of the production function may be suppressed. The estimated production function was restricted by requiring that the sum of the exponents ϕ, ϖ equal unity. The basic implications of such a Cobb-Douglas production function are constant returns to scale and partial elasticities of unity substitution. By assuming profit maximization behavior of the representative firm, it employs each of these inputs where their value of marginal production is equal to their respective prices. With the energy parameter, for instance, the representative firm employs energy at a rate where the following condition is fulfilled:

$$VMP_t^G = P_t^G, \tag{12}$$

where VMP_t^G denotes value of marginal production of energy and P_t^G represents the energy price[6]. We obtain the following demand equations for labor and energy inputs, respectively:

$$L_t = \varphi Q_t \left(\frac{W_t}{P_t^C} \right)^{-1}, \tag{13}$$

$$G_t = \varpi Q_t \left(\frac{P_t^G}{P_t^C} \right)^{-1}. \tag{14}$$

As in Woodford (2003), we assume that the supplier of each good chooses a price for it at each period and is not constrained in any way by the price that has been charged for the good in the past. This supplier has complete information about current demand and cost conditions. As is typically found in a model of monopolistic competition, it is assumed that each supplier understands that his/her sales depend upon the price charged for his/her goods, according to the demand function:[7]

$$Q_t = Y_t \left(\frac{P_t^{NG}}{P_t^c} \right)^{-1}. \tag{15}$$

The index of aggregate demand Y_t corresponds simply to the representative household's choice of the index C_t. Using Eq. (13) and Eq. (14) we write the representative firm's real total cost function as follows:

$$TC_t = Q_t(\varphi W_t + \varpi P_t^G). \tag{16}$$

The equation above shows that an increase in energy prices raises the representative firm's cost function family, including total cost and real marginal cost (See Section (c) of the Appendix for derivatives).

On the other hand, the Phillips curve (see Section (d) in the Appendix for mathematical works) will be as follows:

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[6] Crude oil prices, in US$ per barrel.

[7] We assumed that the total output Y_t in this economy consists of two subsectors, industrial output Q_t and service output, which is assumed to have been determined out of our model. ($Y_t = Q_t +$ service sector output).

$$\begin{aligned}\pi_t = \left(\frac{1}{\psi}+\omega\right)\left(\iota p_{t-1}^{G}+(1-\iota)p_{t-1}^{NG}\right)-\frac{1}{\psi}\left(p_{t-2}^{c}\right) \\ -\frac{\xi}{\psi}\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_{t-1}-\hat{Y}_{t-1}^{n}\right)\right]+\varepsilon_t\end{aligned}, \tag{17}$$

where ε_t is the expectation shock term, identically distributed with mean zero and uncorrelated with the exogenous variables.[8]

Finally, since there is a state of equilibrium in our model, we have $Y_t = C_t^G + C_t^{NG}$. Using this equation, the New Keynesian IS curve equation yields:

$$Y_t = \left(\frac{1-A}{A}\right)^{A}\frac{\alpha_0\left[\Omega(E_t\pi_{t+1}-E_{t-1}\pi_t)\right]^{\frac{\sigma}{\eta}}\left(W_t\right)^{\frac{1}{\eta}}}{\left(P_t^{NG}\right)^{\frac{A(1-\eta)}{\eta}}\left(P_t^{G}\right)^{\frac{1-A(1-\eta)}{\eta}}\left(L_t\right)^{\frac{\kappa}{\eta}}\left(M_t\right)^{\frac{\sigma}{\eta}}}+C_t^{NG}. \tag{18}$$

Since α_0 contains *b*, which is the log of β (the discount factor of the representative household's utility function), shows that IS is a function of interest rate as well.

The total energy demand in our model is equal to the summation of the representative household's energy consumption and the energy input of the firm, which is shown as q_t^D, so $q_t^D = C_t^G + G_t$. Now by substituting the household energy consumption and firm's energy input in this equation, and by assuming equilibrium in the labor market, we can obtain the total energy demand:

$$q_t^D = \left(\frac{1-A}{A}\right)^{A}\frac{\alpha_0\left[\Omega(E_t\pi_{t+1}-E_{t-1}\pi_t)\right]^{\frac{\sigma}{\eta}}\left(W_t\right)^{\frac{1}{\eta}}}{\left(P_t^{NG}\right)^{\frac{A(1-\eta)}{\eta}}\left(P_t^{G}\right)^{\frac{1-A(1-\eta)}{\eta}}\left(L_t\right)^{\frac{\kappa}{\eta}}\left(M_t\right)^{\frac{\sigma}{\eta}}}+\varpi Q_t\left(\frac{P_t^C}{P_t^G}\right). \tag{19}$$

Then we can write (see section (e) in the Appendix for mathematical works):

$$E_t\pi_{t+1}-E_{t-1}\pi_t = \frac{1}{\psi}\left[\left(\Delta\pi_t\right)-\xi\left(\Delta\vartheta_t\right)\right]. \tag{20}$$

[8] ε_t obtained from the following equation:

$$\varepsilon_t = \xi\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_t-\hat{Y}_t^n\right)+\iota\omega(p_t^G-\iota p_t^{NG})\right]-\xi E_t\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_t-\hat{Y}_t^n\right)+\iota\omega(p_t^G-\iota p_t^{NG})\right]. \tag{1}$$

After this, by substituting Eq. (20) in Eq. (18) and Eq. (19) in order to release the IS curve and final energy demand, the following can be obtained:

$$Y_t = \left(\frac{1-A}{A}\right)^A \frac{\alpha_0 \left(\frac{\Omega}{\psi}\left[(\Delta\pi_t)-\xi(\Delta\vartheta_t)\right]\right)^{\frac{\sigma}{\eta}} (W_t)^{\frac{1}{\eta}}}{\left(P_t^{NG}\right)^{\frac{A(1-\eta)}{\eta}} \left(P_t^{G}\right)^{\frac{1-A(1-\eta)}{\eta}} (L_t)^{\frac{\kappa}{\eta}} (M_t)^{\frac{\sigma}{\eta}}} + C_t^{NG}, \tag{21}$$

$$q_t^D = \left(\frac{1-A}{A}\right)^A \frac{\alpha_0 \left(\frac{\Omega}{\psi}\left[(\Delta\pi_t)-\xi(\Delta\vartheta_t)\right]\right)^{\frac{\sigma}{\eta}} (W_t)^{\frac{1}{\eta}}}{\left(P_t^{NG}\right)^{\frac{A(1-\eta)}{\eta}} \left(P_t^{G}\right)^{\frac{1-A(1-\eta)}{\eta}} (L_t)^{\frac{\kappa}{\eta}} (M_t)^{\frac{\sigma}{\eta}}} + \varpi Q_t \left(\frac{P_t^C}{P_t^G}\right). \tag{22}$$

Eq. (21) and Eq. (22) are final IS curve and final energy demand equations, respectively.

Energy producers

As for the energy producer section, we followed Taghizadeh-Hesary's and Yoshino's (2014) model. Supposing that over the period *t*–1 to *t*, crude oil output or extraction of crude oil is given by q_t^s, we write the following equations:

$$Q_t^s = \sum_{t=0}^{T} q_t^S, \tag{23}$$

$$R_t + Q_t^s = R_{t-1} + Q_{t-1}^s, \tag{24}$$

$$R_t = R_{t-1} - q_t^s. \tag{25}$$

where Q_t^s is the cumulative extraction at the end of period t, and R_t is the proven crude oil reserves at period t. Eq. (25) states that the amount of proven oil is diminishing every year by q_t^S. Eq. (25) is under the condition that there is no new discovery of oil. The cost function is obtained from a convex function, depending negatively on the amount of remaining proven reserves. The so-called stock effect is mainly due to the pressure dynamics affecting petroleum extraction. This type of cost specification is also considered by Livernois and Uhler (1987), Farzin (1992), Favero et al. (1994), and more recently by Taghizadeh-Hesary and Yoshino (2014). Here we present a modified version of it:

$$C_t(q_t^S, R_{t-1}) = \alpha\left(q_t^S\right) - \frac{1}{2}\beta(R_{t-1})^2 > 0, \ \alpha > 0, \ \beta > 0. \tag{27}$$

The first part of this cost function $\alpha\left(q_t^S\right)$ represents extraction cost, and the second part of it $\frac{1}{2}\beta\left(R_{t-1}\right)^2$ shows scarcity cost. Crude oil suppliers will choose an extraction profile to maximize the discounted stream of profits over the life of the field.

$$\text{Max}\sum_{t=0}^{T}\theta^t\left[\pi_t(q_t^S, R_{t-1})\right],, \tag{28}$$

s.t.

$$\left(R_t - R_{t-1}\right) = -q_t^s, \tag{29}$$

$$\theta = 1/(1+r+\omega); \quad r > 0. \tag{30}$$

where θ is the subjective rate of discount, and ω is the risk premium. We write the profit equation for a crude oil producer, which is the function of expected possession price at time *t*, in relation to the output of crude oil:

$$\Pi_t = \theta\left[e_t E_{t-1}\left(P_t^G\right)q_t^S - \alpha\left(q_t^s\right) + \frac{1}{2}\beta\left(R_{t-1}\right)^2\right], \tag{31}$$

where $E_{t-1}P_t^G$ is the expected real price of crude oil in US dollars per barrel, e_t denotes the real effective exchange rate of dollars since the oil producer supplies the product to customers in the US and receives dollars in return. The exchange rate is the first channel through which monetary policies affect the supply side of the crude oil market. By assuming profit maximization behavior by the oil producer in an oligopolistic market, the optimal oil supply equation is derived as follows:

$$q_t^S = -\frac{e_t E_{t-1}\left(P_t^G\right) + \beta\left(R_{t-1}\right) - \alpha}{e_t E_{t-1}\left(\partial P_t^G / \partial q_t^s\right)}. \tag{32}$$

As we know, $\left(\partial P_t^G / \partial q_t^s\right) \leq 0$ means that when the supply of oil increases its price declines, and $\left(\partial q_t^s / \partial R_{t-1}\right) \geq 0$ means that larger oil reserves give a larger supply, and finally $\left(\partial q_t^s / \partial P_t^G\right) \geq 0$ means that when the price of crude oil rises, supply will grow larger.

The expected variable $E_{t-1}\left(P_t^G\right)$ is formed rationally: $E_{t-1}\left(P_t^G\right)=E_{t-1}\left(P_t^G \middle| I_{t-1}\right)$. I_{t-1} is the information set in the period $t-1$, upon which expectations $E_{t-1}\left(P_t^G \middle| I_{t-1}\right)$ were based. Following McCallum (1976), the actual and expected prices are expressed as: $P_t^G = E_{t-1}\left(P_t^G\right)+\eta_s$, where η_s is a forecast error that is uncorrelated with I_{t-1}. In addition, as in Hausman et al. (1987) and Revankar and Yoshino (1990), we can obtain the estimated residual from our crude oil demand equation as the explanatory variable $\hat{u}_d$. We rearrange Eq. (32) by substituting for $E_{t-1}\left(P_t^G \middle| I_{t-1}\right)$. Later in our empirical section, we need to add $\hat{u}_d$ to our supply equation, which acts as the information set.

$$q_t^S = -\frac{e_t E_{t-1}\left(P_t^G \middle| I_{t-1}\right)+\beta\left(R_{t-1}\right)-\alpha}{e_t E_{t-1}\left(\partial P_t^G / \partial q_t^s\right)} \tag{33}$$

As the Hotelling rule states (Hotelling 1931), the price of net marginal extraction cost of resources (here α) is expected to rise with the discount rate, r. This is the second channel through which monetary factors have an effect on the energy supply side of our model. As previously stated, exchange rate is the first channel.[9] Therefore, the supply of crude oil is a function of the following: expected price, proven crude oil reserves and monetary factors.

2.3. Monetary policies and crude oil prices

Determining which side is affected more by oil prices makes it possible to clarify the ways in which monetary policy impacts the supply and demand sides of the oil market. Bernanke et al. (1997) determine that the Federal Reserve raises interest rates too much in response to high oil prices, a practice that depresses economic activity beyond the negative effect of the oil price shocks. Several papers, however, critically reevaluate Bernanke

[9] Since oil is expected to be depleted at time *T*, it must be that $E_{T-1}(q_T^s)=E_{T-1}(R_{T-1}-R_T)$ and $E_T(q_{T+1}^s)=0$. That is, in the period after the last barrel of oil is extracted, extraction of oil must be equal to zero. β is a function of the interest rate, so the resulting implicit function for crude oil supply is : $q_t^S = n(P_t^G, i_t, e_t, R_{t-1})$; where i_t is the interest rate at time t.

et al. (1997). For example, Leduc's and Sill's (2004) findings approximated the Federal Reserve's behavior starting in 1979, showing that monetary policy contributes to an approximate 40% drop in output following a rise in oil prices. In a more recent research study, Kormilitsina (2011) used an estimated dynamic stochastic general equilibrium model with the demand for oil to contrast the Ramsey optimum with estimated monetary policy. This study found that monetary policy amplified the negative effects of the oil price shock. In their 2014 research, Taghizadeh-Hesary and Yoshino (2014) developed a global oil model and found significant impacts from the US money market rates as the key interest rate on the demand side of the global oil market, which raised oil prices even higher. Aggressive monetary policies led to low interest rates, credit demand increase, and aggregate demand expansion, all of which contributed to increase of oil prices. According to this research, oil demand was significantly influenced by interest rates, a key factor of monetary policies.

Monetary policies affect oil prices through a number of channels, including interest rates and exchange rates. Channels of interest rate transmission could be completely described by classical monetarism, as well as in modern literature such as the Keynesian IS-LM model. Easing interest rates increase both the demand for credit and aggregate demand, including the demand for commodities. This increased demand for commodities also includes energy demand, especially for crude oil and derivatives because they are major energy carriers.

As for the exchange rate transmission channel, most oil sales throughout the world are denominated in dollars. This means that a depreciation of the dollar would make oil imports cheaper in non-dollar-denominated currencies, raising oil imports and oil demand. Another exchange rate channel is the depreciation of the dollar leading to an appreciation of non-dollar-denominated financial assets. Most global financial assets are in non-dollar denominated currencies and would subsequently raise world oil demand because of the wealth effect.

The relationship between interest rates and crude oil prices is asymmetric. During 1981–2011, average oil prices accelerated from about $35 per barrel in 1981 to beyond $111 per barrel in 2011. At the same time, average US money market rate decreased from 16.7% per annum in 1981 to about 0.1% per annum in 2011 (Taghizadeh-Hesary and Yoshino 2014).

In this paper we clarify this impact on both oil demand and supply, and answer the question of whether, as in Bernanke et al. (1997), interest rates need to be reduced in response to increasing oil prices, or, as in Hamilton and

Herrera (2004), Kormilitsina (2011), Taghizadeh-Hesary and Yoshino (2014, 2015, 2016), Yoshino and Taghizadeh-Hesary (2014) whether stability in oil markets cannot be achieved unless monetary policy is restrained, and real interest rates become significantly positive.

3. EMPIRICAL ANALYSIS

3.1. Data

We use annual data from 1960 to 2011. As for the explanation of the data that we used for each variable, all are summarized in Table 2.

In order to evaluate the stationarity of all series, we used an augmented Dickey–Fuller (ADF) test. The results that we found imply that the consumption of non-energy, the inflation rate, and the GDP gap series were stationary in their level during this period. This implies a stable structure that helped to maintain the consumption of non-energy around a stationary level. All remaining series, except the three above, were non-stationary in level. However, when we applied the unit root test to the first difference of log-level variables, we were able to reject the null hypothesis of unit roots for each of the variables.

These results suggest that except for the consumption of non-energy, the inflation rate, and the GDP gap series, other variables each contain a unit root. Once the unit root test was performed and it was discovered that the variables are non-stationary in level and stationary in first differences level, they were integrated of order one. Hence, they will appear in our simultaneous equation model (SEM) in first differenced form.

Table 2

Variables and data

Notation	Variable	Data
1	2	3
π_t	Inflation rate	US consumer price inflation rate (all urban consumers)
$\hat{Y}_t - \hat{Y}_t^n$	GDP gap	Differences in US GDP before and after Hodrick-Prescott filter
L_t	Labor supply	Average weekly hours in private nonagricultural industries of the US
M_t	Household's money holding	US Money supply (M1)
W_t	Household's nominal wage per hour working	Average hourly earnings in private nonagricultural industries of the US

1	2	3
P_t^c	Consumer price index (CPI)	US consumer price (all urban consumers)
P_t^{NG}	Price of non-energy commodities	US consumer price index – all urban consumers – all items excluding food and energy
P_t^G	Prices of energy (oil)	Average of UK Brent and UAE Fateh oil price indexes (2005=100)
C_t^{NG}	Consumption of non-energy commodities	US real personal consumption expenditures excluding food and energy
r_t	Interest rate	US money market rate
Q_t	Firms output	US industrial production index
Y_t	GDP of oil importer country	US gross domestic product
q_t^D	Total energy (oil) demand	US crude oil consumption
q_t^s	Energy (oil) output or extraction	US crude oil consumption[10]
e_t	Exchange rate (value of US dollar to energy exporter's currency)	US dollar effective exchange rate
R_t	Amount of proven reserves of crude oil	World proven crude oil reserves[11]
$\hat{u}_d$	Demand residual	Demand residual
Z_{1973}, Z_{1979}	Dummy variables	Two dummy variables for two major oil shocks 1973 and 1979

Notes: UAE = United Arab Emirates, US = United States.

Source: compiled by authors.

3.2. Empirical results

It is necessary to run a regression to assess channels of transmission of oil price movements to macroeconomic variable, and to evaluate the impact of monetary factors such as interest rates and exchange rates on the oil market as well. For this reason, we ran the regression for our SEM, which consists of four equations: (i) energy demand, (ii) energy supply, (iii) IS curve, and (iv) the Phillips curve. For simplification, their implicit functions are mentioned below *(*definitions of all variables used are explained in Table 2):

[10] We assumed equilibrium in the crude oil market, so we let consumption be equal to output, and we used the same data for both (Taghizadeh-Hesary and Yoshino 2014).

[11] Proven reserves at any given point in time are defined by quantities of oil that geological and engineering information indicate with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions (Mohaddes 2012).

Energy demand:

$$q_t^D = q_t^D(P_t^G, P_t^{NG}, L_t, W_t, M_t, r_t, \hat{Y}_t - \hat{Y}_t^n, C_t^{NG}), \tag{34}$$

Energy supply:

$$q_t^s = q_t^s(P_t^G, e_t, r_t, R_{t-1}, \hat{u}_d, Z_{1973}, Z_{1979}), \tag{35}$$

IS curve:

$$Y_t = Y_t(Y_{t-1}, P_t^G, P_t^{NG}, W_t, L_t, r_t, M_t, Q_t), \tag{36}$$

New Keynesian Phillips curve (NKPC):

$$\pi_t = \pi_t(\pi_{t-1}, \hat{Y}_t - \hat{Y}_t^n, P_t^G, P_t^{NG}). \tag{37}$$

The estimation of our SEM can be done by (i) two-stage least square (2SLS), (ii) three-stage least square (3SLS), or (iii) weighted two-stage least square (W2SLS). 2SLS, 3SLS, and W2SLS are instrumental-variable estimation methodologies (Taghizadeh-Hesary et al. 2013). We used the Akaike information criterion (AIC) to select the lag orders in which the maximum lag is set to 2 lags of each variable, and to get more rational results, we used the system method of estimation: a weighted two-stage least square (W2SLS).

Our results for oil demand price elasticity agree more with those researchers who found low values for oil demand price elasticities and suggest a demand price elasticity of –0.007 (significant). This means that an increase in oil prices by 100 base points would reduce oil demand by 0.7%. The reason for this low elasticity is because firms and consumers cannot change their production or consumption patterns immediately, the elasticity of their demand to oil prices is low, and from this assumption we expect that the effects of higher oil prices on GDP might be small as well (at least initially).

Our empirical results confirm this expectation, as the coefficient of oil prices in our IS curve equation comes to –0.0008, which is economically small and statistically significant. In this case, the oil price shocks will have a slight impact on the US GDP. However, the production of energy-intensive goods in this country may cause a substantial reallocation of labor, which – if costly – can have a large impact on the production of this sector of economy.

For demand price elasticities, Gately and Huntington (2002) found between –0.12 and –0.64 for both OECD and non-OECD countries, and Krichene's (2006) results were between –0.03 and –0.08 for various countries in the short run. His long-term price elasticity was significantly low: 0.05 in 1918–1999, 0.13 in 1918–1973, and almost zero during 1973–1999.

Table 3

Empirical results, 1962–2011

Notation	CE	T-statistics	Notation	CE	T-statistics
Energy Demand q_t^D			Energy Supply q_t^s		
P_t^G	–0.007	–5.02**	P_t^G	0.003	3.64**
P_t^{NG}	–0.16	–3.78**	e_t	0.28	1.10
L_t	–1.34	–2.47*	r_t	–0.02	–2.62**
W_t	0.28	2.94**	R_{t-1}	0.53	0.99
M_t	0.07	0.48	$\hat{u}_d$	4.36	1.37
r_t	–0.07	–5.40**	Z_{1973}	0.29	3.85**
$\hat{Y}_t - \hat{Y}_t^n$	0.02	0.10	Z_{1979}	0.25	3.55**
C_t^{NG}	0.60	5.39**			
Demand side of economy IS curve (Y_t)			Supply side of economy NKPC (π_t)		
Y_{t-1}	0.81	14.36**	π_{t-1}	0.95	9.61**
P_t^G	–0.0008	–2.01*	$\hat{Y}_t - \hat{Y}_t^n$	–0.59	–3.88**
P_t^{NG}	–0.66	–2.02*	P_t^G	–0.00004	–0.55
W_t	0.04	0.25	P_t^{NG}	0.001	0.57
L_t	0.30	3.77**			
r_t	0.0001	0.10			
M_t	0.15	3.23**			
Q_t	0.34	2.10*			

CE = coefficient, * indicates significance at 5%, ** indicates significance at 1 %, NKPC = New-Keynesian Phillips Curve.

Note: Included observations: 50. Total system (balanced) observations: 200. Estimation method: Two-stage least squares.

Source: compiled by authors.

Mohaddes (2013) found –0.15 for the short-run price elasticity of global oil demand. More recently, Taghizadeh-Hesary and Yoshino's (2014) results suggest a price elasticity for global oil demand of –0.08 (significant), –0.10 (significant), and –0.05 (significant) for 1960–2011, 1960–1980, and 1980–2011, respectively. We found a value of 0.003 for oil supply price elasticity. This elasticity was significant but economically smaller than demand elasticity, which indicates that supply is more rigid.

As for transmission channels of higher oil prices to GDP, our results are in line with Hamilton (1988), suggesting that oil price shocks induce recessions mainly because of a reduction on the demand side of the economy (the aggregate demand curve shifts more than the aggregate supply curve; Figure 3). However, Hamilton suggests that this decrease in demand is mainly due to an increase in uncertainty, along with a rise in the operating costs of certain durable goods. This increase reduces demand for durable goods and investments. Other papers that support our findings are Lee and Ni (2002), who showed that oil price shocks mainly affect the demand side of the economy as well. Their paper suggests that oil price shocks influence economic activity possibly by delaying purchasing decisions of durable goods. Also, Bernanke (2006) showed that an increase in energy prices slows economic growth primarily through its effects on consumer spending and demand side.

Our findings are in contrast with Rasche and Tatom (1977), Bruno (1984), and more recently with DePratto et al. (2009), who claimed that energy prices affect the economy primarily through the supply side channel (their findings are in line with Figure 2). They found that higher oil prices have temporary negative effects on both the output gap and on trend growth, and they did not find significant effects on the demand side. Their results support the notion that higher oil prices have effects similar to negative technology shocks, in that higher oil prices lower firm output in terms of value-added for a given input of capital and labor. Our results for the Phillips curve, which is representative of the supply side of the economy in our model, do not show any significant association between the inflation rate and higher oil prices. This conclusion rejects the hypothesis that high oil prices transmit to the economy through supply side (aggregate supply curve).

As stated earlier, Figure 3 shows that higher oil prices are transmitted to the economy mainly through demand side (aggregate demand movements are greater than aggregate supply shifts). The main results are lower GDP and lower prices. Our empirical results, in line with Figure 3, arrive at the coefficient with negative sign for oil prices in our IS curve equation, which is statistically significant. This means that higher oil prices lead to a decline in GDP. On the other hand, however, the coefficient of oil prices in our Phillips curve is non-significant, but the fact that it is negative shows that higher oil prices reduce general price levels because of lower consumption (lower demand). These are all in line with Figure 3 and with our theoretical analysis.

Monetary policy, as mentioned earlier, tends to affect oil prices through two main channels: interest rates and exchange rates. Our regressions establish that interest rates play a significant role in affecting supply and demand for oil. For the demand side of the oil market in our model, the interest rate coefficient shows a value of –0.07. This means that a decrease in interest rates by 100 base points would raise oil demand by 7%. This indicates that expansionary monetary policies lead to low interest rates and credit demand increase, that would raise the demand for oil because it becomes cheaper to get a loan for capital, raising demand for other input factors. This also increases speculative demand. In the supply side of the crude oil market, we also found a significant value of –0.02 for interest rates. Put simply, this means that a decrease in interest rates by 100 base points would raise oil supply by 2%, a finding that is in line with Hotelling's theory, which claims that lower interest rates reduce the marginal cost of production. Because the scarcity cost does not have a large effect, oil supply increases. This channel of transmission is clearly shown in Eq. (33) of our model. However, the increase in the demand side is larger than the increase in the supply side, so we can expect to have surplus demand in the market following easy monetary policies. The result is skyrocketing crude oil prices, which inhibit economic growth.

As for the exchange rate, results show that the impact of exchange rate depreciations on the oil market was not significant. These results are in line with Taghizadeh-Hesary and Yoshino (2014), who found that the oil market was stable to exchange rate fluctuations during 1960–2011.

CONCLUSIONS

In the theoretical model presented in this paper, changes in the oil price were transmitted to macroeconomic variables through supply (aggregate supply curve) and demand (aggregate demand curve). In particular we allowed oil to shift the IS curve to proxy for temporary demand-side effects, and to affect the Phillips curve to capture inflationary effects through the supply side. This phenomenon creates destructive effects on the growth rate. In the empirical section we conclude that oil price movements affect the economy through the demand channel (in line with Hamilton 1988 and

Bernanke 2006) by reducing household consumption expenditures (aggregate demand movements are greater than aggregate supply shifts; Figure 3). Unlike some earlier studies (Rasche and Tatom 1977, Bruno 1984, DePratto et al. 2009), we could not find statistically significant effects on the supply side (aggregate supply curve).

As for the effect of monetary policies on oil markets, we found that aggressive monetary policies led to low interest rates, credit demand increase, and aggregate demand expansion, which all raised oil prices. We found that oil demand was significantly influenced by interest rates, a key factor of monetary policies (in line with Kormilitsina 2010, Taghizadeh-Hesary and Yoshino 2014, Yoshino and Taghizadeh-Hesary 2014), in contrast with Bernanke et al. (1997). Unlike some earlier studies, we found that low interest rates had an impact on oil supply expansion as well, which was statistically significant but economically smaller than their impact on the demand side of the oil market. The result from this interest rate phenomenon is skyrocketing crude oil prices, which inhibit economic growth. We argue that stability in oil markets cannot be achieved unless monetary policy is restrained, and real interest rates become significantly positive.

As for elasticities in the oil market, our results for oil demand price elasticity agree more with the findings of researchers who arrived at low elasticity values. We also found that the supply of oil is more inflexible to prices, compared to the demand.

APPENDIX

(a) Euler equation, money demand and labor supply equations (log-linearized version)

The log-linearized versions of equations (5)–(7) are as follows:

$$c_t = -\frac{b}{\eta} + E_t c_{t+1} + \frac{1}{\eta} E_t \pi_{t+1}; \quad b = Log\beta, \quad E_t \pi_{t+1} = E_t p^c_{t+1} - p^c_t, \tag{1}$$

$$m_t = \frac{1}{\sigma} p^c_t + \frac{\eta}{\sigma} c_t + \frac{\nu}{\sigma}; \quad \nu = Log\chi, \tag{2}$$

$$l_t = \frac{1}{\kappa}\left(w_t - p^c_t - \eta c_t\right). \tag{3}$$

The lowercase letters denote the logarithms of the corresponding uppercase variables. By solving these three equations for c_t which is consumption in logarithmic form, the consumption equation yields:

$$c_t = \frac{-b+\nu}{\eta} + E_t c_{t+1} + \frac{1}{\eta} E_t \pi_{t+1} - \frac{\sigma}{\eta} m_t + \frac{1}{\eta} w_t - \frac{\kappa}{\eta} l_t. \tag{4}$$

(b) Household energy consumption

Since earlier in Eq. (1) of section (a) of the Appendix we had written $E_t \pi_{t+1} = E_t\left(p^c_{t+1}\right) - p^c_t$, here we convert it back, and substitute the right-hand side of it in Eq. (4) of section (a) of the Appendix in order to release energy prices and non-energy prices from p^c_t. We log-linearize the CPI equation (Eq. 2) as follows:

$$\begin{aligned} &p^c_t = \varepsilon - A\left(a - p^{NG}_t\right) + \left(A-1\right)\left(z - p^G_t\right); \\ &\varepsilon = Log\lambda, \quad a = LogA, \quad z = Log(1-A) \end{aligned} \quad . \tag{1}$$

By substituting it and the expected value of Eq. (2) of section (a) of the Appendix for t+1 in Eq. (4) of section (a) in the Appendix, the logarithmic form of the household consumption equation yields:

$$\begin{aligned} c_t = &\frac{-b-\varepsilon-(A-1)z+Aa}{\eta} - \frac{A}{\eta} p^{NG}_t \\ &+\frac{(A-1)}{\eta} p^G_t + \frac{\sigma}{\eta} E_t m_{t+1} - \frac{\sigma}{\eta} m_t + \frac{1}{\eta} w_t - \frac{\kappa}{\eta} l_t \end{aligned} \quad . \tag{2}$$

Substituting the anti-log of Eq. (2) of section (b) of the Appendix into Eq. (2) of footnote 22, gives the demand of representative household for energy yields.

(c) The Phillips curve (part 1)

Real marginal cost is written as follows:

$$s_t = \left(\varphi W_t + \varpi P_t^G\right). \tag{1}$$

Following Woodford's (2003) analysis, we write the equation below which shows the relationship between marginal cost of supply and output levels:

$$\hat{s}_t = \omega \hat{Q}_t + \sigma^{-1}\hat{Y}_t - \left(\omega + \sigma^{-1}\right)\hat{Y}_t^n, \tag{2}$$

where $\omega > 0$ and $\sigma > 0$. Letting $\overline{Y}$ be the constant level of output in a steady state, and Y_t^n be level of output in full employment, we define $\hat{Q}_t = \log\left(Q_t / \overline{Y}\right)$, $\hat{Y}_t = \log\left(Y_t / \overline{Y}\right)$, $\hat{Y}_t^n = \log\left(Y_t^n / \overline{Y}\right)$, and $\hat{s}_t = \log\left(\mu s_t\right)$, where $\mu = \theta/(\theta - 1) > 1$ is the seller's desired markup. Substituting Eq. (2) in section (c) of the Appendix in the following inflation equation from Calvo (1983) produces the following results:

$$\pi_t = \xi \hat{s}_t + \psi E_t \pi_{t+1}, \tag{3}$$

$$\pi_t = \left[\omega \hat{Q}_t + \sigma^{-1}\hat{Y}_t - \left(\omega + \sigma^{-1}\right)\hat{Y}_t^n\right]\xi + \psi E_t \pi_{t+1}. \tag{4}$$

Dividing Eq. (15) by $\overline{Y}$ and obtaining the log-linearization of this equation results in the following:

$$\hat{Q}_t = \log\left[\frac{Y_t}{\overline{Y}}\left(\frac{P_t^c}{P_t^{NG}}\right)\right] = \hat{Y}_t + p_t^c - p_t^{NG}. \tag{5}$$

The corresponding log-linear approximation to the aggregate price index is as follows:

$$p_t^c = \iota p_t^G + (1 - \iota) p_t^{NG}. \tag{6}$$

Substituting the log linear aggregate price index (Eq. (6) of section (c) of the Appendix) along with Eq. (5) of section (c) of the Appendix into Eq. (4) of section (c) of the Appendix yields a New-Keynesian Phillips curve:

$$\pi_t = \xi\left[\left(\omega + \sigma^{-1}\right)\left(\hat{Y}_t - \hat{Y}_t^n\right) + \omega\left(\iota p_t^G - \iota p_t^{NG}\right)\right] + \psi E_t \pi_{t+1}. \tag{7}$$

We followed the Blanchard and Kahn (1980) method for rational expectations:

$$E_t\pi_{t+1} = \frac{1}{\psi}\pi_t - \frac{\xi}{\psi}\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_t - \hat{Y}_t^n\right) + \omega\left(\iota p_t^G - \iota p_t^{NG}\right)\right]. \tag{8}$$

Then for the previous period we have:

$$E_{t-1}\pi_t = \frac{1}{\psi}\pi_{t-1} - \frac{\xi}{\psi}\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_{t-1} - \hat{Y}_{t-1}^n\right) + \omega(\iota p_{t-1}^G - \iota p_{t-1}^{NG})\right]. \tag{9}$$

Thus we obtain the E_{t-1} value of Eq. (7) of section (c) of the Appendix, which we can write in for the $E_t\pi_{t+1}$ results:

$$\begin{gathered} E_t\pi_{t+1} = \frac{1}{\psi}E_{t-1}\pi_t \\ -\frac{\xi}{\psi}E_{t-1}\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_t - \hat{Y}_t^n\right) + \omega\left(\iota p_t^G - \iota p_t^{NG}\right)\right] \end{gathered}. \tag{10}$$

After substituting $E_{t-1}\pi_t$ from Eq. (9) of section (c) of the Appendix with Eq. (10) of section (c) of the Appendix, and then setting Eq. (8) of section (c) of the Appendix and Eq. (10) of section (c) of the Appendix as equal to the Phillips curve yields, however, it becomes apparent that this is not the final version and we need to do some more work on it.

(d) The Phillips curve (part 2)

Initial version of Phillips curve:

$$\pi_t = \frac{1}{\psi}\pi_{t-1} - \frac{\xi}{\psi}\left[\left(\omega+\sigma^{-1}\right)\left[\hat{Y}_{t-1} - \hat{Y}_{t-1}^n\right] + \omega\left(\iota p_{t-1}^G - \iota p_{t-1}^{NG}\right)\right] + \varepsilon_t\,. \tag{1}$$

From Eq. (6) of section (c) of the Appendix, we write the inflation rate in t–1 and substitute it in Eq. (1) of section (d) of the Appendix, making it so that the final Phillips curve yields the results in Eq. (17).

(e) Equation 20. Derivations

Considering the initial version of our Phillips curve (Eq. (1) in section (d) of the Appendix) by solving for $E_t\pi_{t+1} - E_{t-1}\pi_t$:

$$E_t\pi_{t+1} - E_{t-1}\pi_t = \frac{1}{\psi}\left(\pi_t - \pi_{t-1}\right) - \frac{\xi}{\psi}\begin{pmatrix} \left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_t - \hat{Y}_t^n\right) + \iota\omega\left(p_t^G - \iota p_t^{NG}\right)\right] - \\ \left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_{t-1} - \hat{Y}_{t-1}^n\right) - \iota\omega\left(p_{t-1}^G - \iota p_{t-1}^{NG}\right)\right] \end{pmatrix}. \tag{1}$$

We assume the equation:

$$\left[\left(\omega+\sigma^{-1}\right)\left(\hat{Y}_t - \hat{Y}_t^n\right) + \iota\omega\left(p_t^G - \iota p_t^{NG}\right)\right] = \vartheta_t \,. \tag{2}$$

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Received: July 2014, revised: May 2018