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Abstract

An exogenous oil price shock raises inflation and contracts output, similar to a negative productivity shock. In the standard New Keynesian model, however, this does not generate a tradeoff between inflation and output gap volatility: under a strict inflation targeting policy, the output decline is exactly equal to the efficient output contraction in response to the shock. We propose an extension of the standard model in which the presence of a dominant oil supplier (OPEC) leads to inefficient fluctuations in the oil price markup, reflecting a dynamic distortion of the economy´s production process. As a result, in the face of oil sector shocks, stabilizing inflation does not automatically stabilize the distance of output from first-best, and monetary policymakers face a tradeoff between the two goals.

JEL classification: E31, E32, E52, Q43.

Keywords: oil shocks, inflation-output gap tradeoff, dominant firm.

1 Introduction

Over the past five years the price of oil has tripled in real terms, from \$20 per barrel in 2002 to \$60 per barrel in 2006 (at constant prices of year 2000). This has rekindled memories of the sharp oil price rises in the 1970-s when the real oil price tripled in 1973 and then again more than doubled in 1979 (see Figure 1). The former oil price hikes coincided with dramatic declines in US GDP growth and double-digit inflation.[1] And while so far the recent oil price build-up has been accompanied with only a modest pick up in inflation and more or less stable GDP growth, it has reignited discussions about the causes and effects of oil price fluctuations, as well as the appropriate policy responses to oil sector shocks (e.g. Bernanke, 2006).

Most of the existing academic and policy-oriented literature treats oil price movements as unexpected exogenous shifts in the price of oil, unrelated to any economic fundamentals. Seen in this way, oil price shocks are the typical textbook example of a supply-side disturbance which raises inflation and contracts output (e.g. Mankiw, 2006). Thus, for a central bank that cares about inflation and output stability, oil price shocks create a difficult policy trade-off: if the central bank raises the interest rate in order to fight off inflation, the resulting output loss will be larger. And if instead it lowers the rate to prevent output from falling, the ensuing inflation rise will be higher. In any case, the central bank simply cannot achieve its dual objective of stabilizing both prices and output at their respective levels before the shock.

Modern theories of the business cycle have questioned the appropriateness of stabilizing output at its level before the shock. In particular, RBC theory points that in response to an exogenous oil price increase — which in that framework is equivalent to a negative productivity shock — the efficient (first-best) level of output declines, as firms find it optimal to scale down production (and households to give up some consumption for additional leisure). An implication of this for a world with nominal rigidities, is that in the face of an oil price shock, the central bank should not attempt to stabilize output, but instead should seek to align the output response with the first-best reaction to the oil price change. That is, it should try to stabilize the *output gap*, defined as the distance between actual output and its efficient level given the shock.

Our first result is to show that in the standard New Keynesian model extended with oil as an additional productive input, if the oil price is taken to be exogenous (or perfectly competitive), then there is no tradeoff between inflation and output gap volatility. In other words, even in the face of oil price shocks, there is a "divine coincidence" in the sense of Blanchard and Galí (2006): a policy of price stability automatically stabilizes the distance of output from first-best. This result is important because, if it is true in general and is not just

[1] In fact, Hamilton (1983) observed that all but one US recessions since World War II (until the time of his publication) were preceded by increases in the price of crude oil.

an artifact of some simplifying assumptions, it implies that the task of central banks is much easier and that monetary policy can focus exclusively on price stability.

Our second contribution is to demonstrate that the above "coincidence" breaks down when one relaxes the assumption of exogenous oil price and models explicitly the oil sector's supply behavior. To show this, we model in general equilibrium the behavior of OPEC as a dominant firm which seeks to maximize profit, internalizing the effect of its supply decision on the oil price. Operating alongside a competitive fringe of price-taking oil suppliers, the dominant oil exporter sells its output to an oil importing country (the US), which uses it to produce final goods.

The steady-state of this environment is characterized by an inefficiently low level of oil supply by OPEC, a positive oil price markup, and a suboptimal level of output in the oil importing country. Importantly, shocks in this setup induce inefficient fluctuations in the oil price *markup*, reflecting a dynamic distortion of the economy's production process. As a result, stabilizing inflation does not fully stabilize the distance of output from first-best, and monetary policy-makers face a meaningful tradeoff between the two goals.[2]

Our model allows us to move away from discussing the effects of exogenous oil price changes and towards analyzing the implications of the underlying shocks that cause the oil price to change in the first place. This is a clear advantage over the existing literature, which treats the macroeconomic effects and policy implications of oil price movements as if they were independent of the underlying source of disturbance.[3] In our case there are four structural shocks — to US total factor productivity, to monetary policy, to oil production technology, and to the total capacity of the competitive fringe, each of which affects the oil price through a different channel. Notably, the effects of each of these shocks on macroeconomic variables, and their policy implications, are quite different. In particular, conditional on the source of the shock, a central bank confronted with the same oil price increase would find it desirable to either raise or lower the interest rate (relative to a standard Taylor-type rule).

Finally, we touch on the debate of the relevant inflation target, that is, "core" versus "headline" inflation. If the central bank targets headline inflation, then it implicitly reacts to movements in energy prices roughly in proportion to the share of energy in CPI. Yet our analysis suggests that oil sector developments affect stabilization performance through a different channel, and as such should be treated separately from the CPI index. In particular, we find that a relevant variable to target is the oil price *markup* (which under the assumptions of our model is related to OPEC's market share). This is quite different from

[2]Rotemberg and Woodford (1996) allow for *exogenous* variation in the oil price markup in a model very different from ours.

[3]See for example Kim and Loungani (1992), Leduc and Sill (2004), and Carlstrom and Fuerst (2005); see Killian (2006) for an exception.

advocating a uniform Taylor-type reaction to changes in the oil *price* (and indeed we show that, in general, the latter policy would not improve much on the benchmark rule which targets inflation only).

The following section presents the model and the baseline calibration; section 3 discusses the steady-state and comparative statics; section 4 analyzes the dynamic properties of the model, including impulse-responses and policy implications; section 5 reports the dependence of the effects of oil sector shocks on the oil share in production as well as on the monetary regime in place; and the last section concludes.

2 The Model

There are two large countries (or regions) — an oil importing and an oil exporting one, and a fringe of small oil exporting countries in the rest of the world. The oil importing country (the US) produces no oil itself but needs it to produce final goods of which it is the only exporter.[4] Oil is a homogenous commodity supplied to the US by two different types of producers: a dominant oil exporter (OPEC) who fully internalizes his effect on the global economy, and a competitive fringe of atomistic exporters, who choose their supply taking prices as given. Oil exporters produce oil only, using as inputs a fraction of the final goods sold to them by the US. In addition, they buy from the US a fraction of final goods which they use for consumption, with the rest of final goods output consumed by the US itself. There is no borrowing across regions (regional current accounts are balanced in each period) and trade is carried out in a common world currency (the dollar).

Two main features distinguish our model from the rest of the literature: the endogeneity of the oil price and the existence of a dominant oil supplier. These assumptions are consistent with a number of observations in the literature regarding the nature of the oil market. In particular, Mabro (1998) argued convincingly that oil demand and the oil price are affected significantly by global macroeconomic conditions.[5] At the same time, Adelman and Shahi (1989) estimated the marginal cost of oil production well below the actual oil price. Indeed, it is obvious that the world's oil industry is not characterized by a continuum of measureless "Mom and Pop" oil extractors. Instead, there is one cartel (OPEC) with more power than any other producer, yet other producers exist and collectively can restrain the exercise of monopoly power by the cartel (Salant, 1976).[6] Empirical evidence by Griffin (1985), Jones (1990), and Dahl

[4] The US accounts for roughly 30% of global output, and 30% of OPEC's oil exports (IMF, 2007).

[5] Moreover, when testing the null hypothesis that the oil price is not Granger-caused collectively by US output, unemployment, inflation, wages, money and import prices, Hamilton (1983) obtained a rejection at the 6% significance level. In the same article he explicitly referred to the possibility that the oil price was affected by US inflation.

[6] Currently OPEC accounts for around 40% of the world's oil production (EIA, 2007).

and Yucel (1991) also suggests that OPEC behavior is closer to that of a cartel than a confederation of competitive suppliers.

2.1 Oil Importing Country

The oil importing country is a canonical sticky price economy with oil included as an additional input in production, monopolistic competition, and Calvo (1983) contracts. We call this country "the US" for short.

2.1.1 Households

The country is populated by a representative household, which seeks to maximize the expected present discounted flow of utility streams,

$$\max E_o \sum_{t=0}^{\infty} \beta^t U(C_t, L_t), \tag{1}$$

subject to a budget constraint. The period utility function depends on consumption, C_t, and labor L_t, and we assume that it takes the form

$$U(C_t, L_t) = \log(C_t) - \frac{L_t^{1+\psi}}{1+\psi}. \tag{2}$$

The period t budget constraint,

$$P_t C_t + B_t R_t^{-1} = B_{t-1} + w_t P_t L_t + r_t P_t \bar{K} + \Pi_t^f, \tag{3}$$

equates nominal income from labor, $w_t P_t L_t$, capital $r_t P_t \bar{K}$, dividends from the final goods firms owned by the household, Π_t^f, and nominally riskless bonds, B_{t-1}, to outlays on consumption, $P_t C_t$, and bonds, $B_t R_t^{-1}$. The aggregate stock of capital which the household rents out to firms is assumed to be constant, $\bar{K}$, normalized to one.

The consumption good C_t is a Dixit-Stiglitz aggregate of a continuum of differentiated goods $C_t(i)$,

$$C_t = \left[\int_0^1 C_t(i)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}} \tag{4}$$

with associated price index,

$$P_t^{1-\epsilon} = \int_0^1 P_t(i)^{1-\epsilon} di \tag{5}$$

where $P_t(i)$ is the price of good i.

The household chooses the sequence $\{C_t, L_t, B_t\}_{t=0}^{\infty}$ in order to maximize the expected present discounted utility (1) subject to the budget constraint (3). In addition, it allocates expenditure among the different goods $C_t(i)$ so as to minimize the cost of buying the aggregate bundle C_t.

2.1.2 Final Goods Sector

Final goods are produced under monopolistic competition with labor, capital, and oil according to

$$Y_t(i) = A_t L_t(i)^{\alpha_1} K_t(i)^{\alpha_2} O_t(i)^{1-\alpha_1-\alpha_2} \tag{6}$$

where A_t denotes aggregate total factor productivity. The latter evolves exogenously according to

$$a_t = \rho_a a_{t-1} + \varepsilon_t^a \tag{7}$$

where $a_t \equiv \log(A_t)$ and $\varepsilon_t^a \sim i.i.d.N.\left(0, \sigma_a^2\right)$.

Individual firms are small and take all aggregate variables as given. In particular, firms take factor prices as given as they compete for inputs on economy-wide factor markets in order to minimize the total cost of production. In addition, firms reset their prices infrequently *a la* Calvo (1983). In each period a constant random fraction θ of all firms is unable to change their price and must satisfy demand at whatever price they posted in the previous period. Whenever they get a chance to change their price $P_t(i)$, firms seek to maximize the expected present discounted stream of profits,

$$\max E_t \sum_{k=0}^{\infty} \theta^k \Lambda_{t,t+k} [P_t(i) Y_{t+k}(i) - P_{t+k} C\left(Y_{t+k}(i)\right)] \tag{8}$$

subject to a downward sloping demand schedule,

$$Y_{t+k}(i) = \left(\frac{P_t(i)}{P_{t+k}}\right)^{-\epsilon} Y_{t+k}, \tag{9}$$

where $Y_{t+k}(i)$ is demand for the output of firm i, $C\left(Y_{t+k}(i)\right)$ is the real cost of producing that output, and $\Lambda_{t,t+k}$ is the discount factor for nominal payoffs.

2.1.3 Monetary Policy

The central bank in the oil importing country is committed to set the nominal interest rate according to the rule

$$\frac{R_t}{\bar{R}} = e^{r_t} \left(\frac{R_{t-1}}{\bar{R}}\right)^{\phi_R} \left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\phi_\pi} \left(\frac{p_{ot}}{p_{ot-1}}\right)^{\phi_o}, \tag{10}$$

where $\bar{R} \equiv \bar{\Pi}/\beta$ and $\bar{\Pi}$ is the target rate of inflation; r_t is an i.i.d. "interest rate shock", distributed normally with mean zero and variance σ_r^2. ϕ_R is an "interest rate smoothing" parameter, and ϕ_π and ϕ_o are policy reaction coefficients.

We allow for a possible non-zero reaction of the central bank to the change in the real price of oil. While our analysis in section 2.6 shows that the welfare-relevant target variable is not this but the oil price *markup*, the latter depends on the current marginal cost of oil production, which we assume to be unobservable by the monetary authority.

2.2 Oil Exporting Countries

Modelling the oil industry as a dominant firm with competitive fringe dates back to Salant (1976). He argued that neither perfect competition, nor a single monopolist owning all the oil, bear much resemblance to the actual structure of the world oil industry. While his focus was on the Cournot-Nash equilibrium of the game between the competitive fringe and the dominant extractor of exhaustible oil, our interest lies in the links between the dominant oil supplier and the oil importer. As we shall see, the existence of competitive oil producers affects in important ways the equilibrium behavior of the dominant oil supplier.

2.2.1 Dominant Oil Exporter

The large oil exporting country, called "OPEC", is populated by a representative household that seeks to maximize its expected present discounted flow of utility streams,

$$\max E_o \sum_{t=0}^{\infty} \beta^t U(\tilde{C}_t), \tag{11}$$

where the period utility function is logarithmic in consumption,

$$U\left(\tilde{C}_t\right) = \log(\tilde{C}_t). \tag{12}$$

The household faces a period budget constraint,

$$P_t \tilde{C}_t = \Pi_t^o, \tag{13}$$

which equates consumption expenditure to dividends from OPEC, Π_t^o, which is wholly owned by the household. As such, the representative household's objective of expected utility maximization is consistent with maximizing the expected present discounted value of the logarithm of real profits from oil production, where period profits are given by[7]

$$\frac{\Pi_t^o}{P_t} = p_{ot} O_t - \tilde{I}_t. \tag{14}$$

OPEC produces oil according to

$$O_t = Z_t \tilde{I}_t, \tag{15}$$

where Z_t is an exogenous productivity shifter, and $\tilde{I}_t$ is an intermediate good used in oil production and bought from the oil importing country. The productivity of OPEC evolves exogenously according to

$$z_t = \rho_z z_{t-1} + \varepsilon_t^z, \tag{16}$$

[7] If we had a single representative houshold - owner of both the final goods firms and the dominant oil firm, a rationalizable objective of the dominant oil firm would be zero profits since that would replicate the efficient (competitive market) equilibrium.

where $z_t \equiv \log(Z_t)$ and $\varepsilon_t^z \sim i.i.d.N\left(0, \sigma_z^2\right)$.

The consumption good $\tilde{C}_t$ and the intermediate good $\tilde{I}_t$ are Dixit-Stiglitz aggregates of a continuum of differentiated goods of the same form (4) and with the same price index (5) as before. OPEC allocates expenditure among the different intermediate and final goods so as to minimize the cost of buying the aggregate bundles $\tilde{I}_t$ and $\tilde{C}_t$. It chooses a level of oil output, so as to maximize the expected present discounted utility of the representative household, subject to the behavior of competitive oil exporters, and households, firms and monetary authority in the US.

2.2.2 Competitive Fringe of Small Oil Exporters

Apart from the dominant oil exporter, in the rest of the world there is a continuum of atomistic oil firms, indexed by $i \in [0, \Omega_t]$. Each firm produces a quantity $X_t(i)$ of oil according to the technology

$$X_t(i) = \xi(i) Z_t \hat{I}_t(i), \tag{17}$$

subject to the capacity constraint,

$$X_t(i) \in [0, \bar{X}], \tag{18}$$

where $[\xi(i) Z_t]^{-1}$ is the marginal cost of oil production of firm i; $1/Z_t$ is a component of marginal cost common to all oil firms, while $1/\xi(i)$ is a constant firm-specific component distributed according to some probability distribution function $F(1/\xi(i))$. The input $\hat{I}_t(i)$ is purchased from the oil importer as is consumption of the representative household owning each oil firm,$\hat{C}_t(i)$, which is equal to the real profit from oil production.[8] Both $\hat{I}_t(i)$ and $\hat{C}_t(i)$ are Dixit-Stiglitz aggregates of differentiated goods analogous to those of the dominant oil firm.

The total mass (or total capacity) of competitive fringe producers Ω_t is allowed to vary according to a stationary stochastic process,

$$\hat{\omega}_t = \rho_\omega \hat{\omega}_{t-1} + \varepsilon_t^\omega \tag{19}$$

where $\hat{\omega}_t \equiv \log\left(\Omega_t/\bar{\Omega}\right)$ and $\varepsilon_t^\omega \sim i.i.d.N\left(0, \sigma_\omega^2\right)$. We make this allowance to capture the fact that some oil fields of the fringe are used up, while new ones are discovered and so the total amount of oil recoverable by the competitive fringe is not constant over time. In section 4 we evaluate the effects of a transitory change in the availability of oil outside OPEC's control on the equilibrium oil price and macroeconomic aggregates. As we will see, it is the only shock in our model which induces a negative correlation between the supply of OPEC and the output of the competitive fringe, a feature of the data which is prominent in the 1980-s and early 1990-s (see figure 10).

[8] We assume perfect risk-sharing among competitive fringe producers.

The produced oil can either be sold at the international price p_{ot}, which the atomistic exporters take as given, or it is lost. Each small supplier chooses the amount of oil to produce in each period so as to maximize profits,

$$\max \{p_{ot}X_t(i) - X_t(i)/\xi(i)\} \tag{20}$$
$$\text{s.t.}$$
$$X_t(i) \in [0, \bar{X}]$$

The existence of competitive producers restrains significantly the exercise of monopoly power by the dominant oil firm. In our case, the measure of non-OPEC competitors (calibrated to match their average market share) reduces the average oil price markup from 20 (in the case of full oil monopoly) to 1.36 times marginal cost (in the case of a "dominant firm"). Moreover, the introduction of a competitive fringe allows us to model transitory shifts in the market share of OPEC. Figure 2 shows that this share has not been constant over the last four decades: it was around 50% in the 1970s, then dropped down to 30% in the 1980s, before recovering to around 40% in the last two decades. Since around 70% of the world's "proven reserves" are under OPEC control (EIA, 2007), some observers suggest that in the absence of any new major oil discoveries or technological advances in non-OPEC countries, the cartel's market share would rise steadily in the future (however, see Adelman (2004) for a forceful refutation of the idea that oil is running out and on the meaninglessness of the concept of "proven reserves").

Most importantly for the oil importing country, the asymmetric distribution of market power between the two types of oil suppliers induces a dynamic markup distortion reflected in variation of the oil price markup in response to all shocks. This breaks the "divine coincidence" between stabilizing inflation and stabilizing the welfare-relevant output gap, creating a tension between the two stabilization objectives.

2.3 Equilibrium Conditions for a Given Oil Supply

2.3.1 Optimality conditions

The first-order optimality conditions of the representative US household are:

$$C_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} C_t \tag{21}$$

$$C_t L_t^{\psi} = w_t \tag{22}$$

$$1 = \beta R_t E_t \left[\frac{C_t}{C_{t+1}} \frac{P_t}{P_{t+1}}\right]. \tag{23}$$

Condition (21) states that the relative demand for good i is inversely related to its relative price. Equation (22) is a standard labor supply curve equating the marginal rate of substitution between consumption and leisure to the real wage; and (23) is a standard consumption Euler equation.

Cost minimization by final goods firms implies

$$w_t L_t(i) = \alpha_1 mc_t Y_t(i) \tag{24}$$

$$r_t K_t(i) = \alpha_2 mc_t Y_t(i) \tag{25}$$

$$p_{ot} O_t(i) = (1-\alpha_1-\alpha_2) mc_t Y_t(i) \tag{26}$$

where w_t is the real wage, p_{ot} is the real price of oil, r_t is the real rental price of capital, and mc_t are real marginal costs, which are common across all firms. The above conditions equate marginal costs of production to the factor price divided by the marginal factor product for each input of the production function for final goods. At the same time, with Cobb-Douglas technology, marginal costs are given by

$$mc_t = \frac{w_t^{\alpha_1} r_t^{\alpha_2} p_{ot}^{1-\alpha_1-\alpha_2}}{A_t \alpha_1^{\alpha_1} \alpha_2^{\alpha_2} (1-\alpha_1-\alpha_2)^{1-\alpha_1-\alpha_2}}. \tag{27}$$

The optimal price-setting decision of firm i implies that the optimal reset price $P_t^*(i)$ satisfies

$$p_t^* \equiv \frac{P_t^*(i)}{P_t} = \frac{N_t}{D_t}, \tag{28}$$

where N_t and D_t are governed by

$$D_t = \frac{Y_t}{C_t} + \beta\theta E_t \left[\Pi_{t+1}^{\epsilon-1} D_{t+1}\right] \tag{29}$$

$$N_t = \mu mc_t \frac{Y_t}{C_t} + \beta\theta E_t \left[\Pi_{t+1}^{\epsilon} N_{t+1}\right] \tag{30}$$

with $\mu \equiv \frac{\epsilon}{\epsilon-1}$. These conditions imply that whenever a firm is able to change its price, it sets it at a constant markup μ over a weighted average of current and expected future marginal costs, where the weights associated with each horizon k are related to the probability that the chosen price is still effective in period k.

All resetting firms face an identical problem and hence choose the same price. Given that the fraction of firms resetting their price is drawn randomly from the set of all firms, and using the definition of the aggregate price index, we have

$$P_t^{1-\epsilon} = \theta P_{t-1}^{1-\epsilon} + (1-\theta) P_t^{\star 1-\epsilon} \tag{31}$$

which implies

$$1 = \theta \Pi_t^{\epsilon-1} + (1-\theta) p_t^{\star 1-\epsilon}. \tag{32}$$

Denoting the relative price dispersion by

$$\Delta_t \equiv \int_0^1 \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} di, \tag{33}$$

one can derive a law of motion for this measure as

$$\Delta_t = \theta \Pi_t^{\epsilon} \Delta_{t-1} + (1-\theta) p_t^{\star -\epsilon}. \tag{34}$$

Finally, each competitive fringe exporter finds it profitable to produce oil if and only if the current market price of oil p_{ot} is greater than his marginal cost. Thus, competitive oil firm i produces $\bar{X}$ if $[\xi(i) Z_t]^{-1} \leq p_{ot}$ and zero otherwise.

2.3.2 Aggregation

Aggregating the demand for labor, capital and oil by final goods firms yields,

$$L_t = \int_0^1 L_t(i)di \tag{35}$$

$$K_{dt} = \int_0^1 K_t(i)di \tag{36}$$

$$O_{dt} = \int_0^1 O_t(i)di \tag{37}$$

In turn, aggregate demand for final goods output is given by,

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}} di\right]^{\frac{\epsilon}{\epsilon-1}}. \tag{38}$$

Analogous expressions describe the aggregate consumption and intermediate goods import components of aggregate demand for each country.

The above, together with (9), imply that the following aggregate demand relationships hold,

$$p_{ot}O_{dt} = (1-\alpha_1-\alpha_2)mc_tY_t\Delta_t \tag{39}$$

$$w_tL_t = \alpha_1 mc_tY_t\Delta_t \tag{40}$$

$$r_tK_{dt} = \alpha_2 mc_tY_t\Delta_t, \tag{41}$$

where aggregate output satisfies

$$Y_t = \frac{A_t}{\Delta_t} L_t^{\alpha_1} K_{dt}^{\alpha_2} O_{dt}^{1-\alpha_1-\alpha_2}. \tag{42}$$

Notice in particular the distortionary effect of aggregate price dispersion in (42), which acts like a tax on aggregate output, in a way similar to a negative productivity shock.

Aggregate real profits of final goods firms in the oil importing country are given by,

$$\frac{\Pi_t^f}{P_t} = Y_t - p_{ot}O_{dt} - w_tL_t - r_t\bar{K}. \tag{43}$$

Finally, the amount of oil produced by the competitive fringe as a whole is given by

$$X_t \equiv \int_0^{\Omega_t} X_t(i)di = \Omega_t F(p_{ot}Z_t) \tag{44}$$

To simplify, we assume that the idiosyncratic component of marginal costs $1/\xi(i)$ is distributed uniformly in the interval $[a, b]$. In that case

$$X_t = \begin{cases} \Omega_t\bar{X}, & p_{ot}Z_t > b \\ \Omega_t\bar{X}\frac{p_{ot}Z_t-a}{b-a}, & a < p_{ot}Z_t \leq b \\ 0, & p_{ot}Z_t \leq a \end{cases} \tag{45}$$

We further assume without loss of generality[9] that $a = 0$ and normalize $b = \bar{X} > 1$ which we choose sufficiently large that at least some competitive fringe producers (or potential entrants) are always priced out of the market by the dominant oil firm. With these assumptions the output of the competitive fringe is a product of the price of oil (p_{ot}), productivity of the oil sector (Z_t), and a component related to the depletion and discovery of new oil deposits by the competitive fringe (Ω_t):

$$X_t = \Omega_t p_{ot} Z_t. \tag{46}$$

2.3.3 Market clearing

Bonds are in zero net supply and the supply of capital is fixed at the aggregate level. Hence, in equilibrium, we have

$$B_t = 0 \tag{47}$$

$$K_{dt} = \bar{K} = 1 \tag{48}$$

which, substituting into the budget constraint of the oil importing country's household, implies

$$C_t = w_t L_t + r_t \bar{K} + \frac{\Pi_t^f}{P_t}. \tag{49}$$

Substituting aggregate real profits from (43) in the above equation yields,

$$C_t = Y_t - p_{ot} O_{dt}. \tag{50}$$

Further, aggregate oil demand is equal to the supply of the dominant oil firm plus the aggregate output of the competitive fringe of oil exporters:

$$O_{dt} = O_t + X_t. \tag{51}$$

Finally, the aggregate consumption of small oil exporters equals their aggregate real profits,

$$\hat{C}_t = p_{ot} X_t - \hat{I}_t \tag{52}$$

With these conditions we can verify that the aggregate resource constraint holds,

$$Y_t = C_t + \tilde{C}_t + \tilde{I}_t + \hat{C}_t + \hat{I}_t, \tag{53}$$

whereby global final goods output is equal to global final goods consumption plus global intermediate input purchases.

[9] Our main results are unaffected if we assume instead that OPEC is the most efficient oil supplier by setting $a = 1$.

2.4 The Dominant Oil Exporter's Problem

We assume that OPEC solve a Ramsey-type problem. Namely, they seek to maximize the expected welfare of the representative household-owner of OPEC, subject to the behavior of all other agents and the global resource constraint. Formally, in our setup this is equivalent to maximizing the expected present discounted value of the logarithm of oil profits,

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \log \left[p_{ot} O_t - O_t / Z_t \right] \tag{54}$$

subject to the constraints imposed by the optimal behavior of the competitive fringe,

$$X_t = \Omega_t p_{ot} Z_t, \tag{55}$$

of households,

$$w_t = C_t L_t^{\psi} \tag{56}$$

$$1 = \beta R_t E_t \left[\frac{C_t}{C_{t+1}} \frac{P_t}{P_{t+1}} \right], \tag{57}$$

and final goods firms in the oil importing country,

$$D_t = \frac{Y_t}{C_t} + \beta\theta E_t \left[\Pi_{t+1}^{\epsilon-1} D_{t+1} \right] \tag{58}$$

$$N_t = \mu m c_t \frac{Y_t}{C_t} + \beta\theta E_t \left[\Pi_{t+1}^{\epsilon} N_{t+1} \right] \tag{59}$$

$$1 = \theta \Pi_t^{\epsilon-1} + (1-\theta) \left(\frac{N_t}{D_t} \right)^{1-\epsilon} \tag{60}$$

$$\Delta_t = \theta \Pi_t^{\epsilon} \Delta_{t-1} + (1-\theta) \left(\frac{N_t}{D_t} \right)^{-\epsilon} \tag{61}$$

$$p_{ot} = (1 - \alpha_1 - \alpha_2) m c_t Y_t \Delta_t / \left(O_t + X_t \right) \tag{62}$$

$$L_t = \alpha_1 m c_t Y_t \Delta_t / w_t \tag{63}$$

$$Y_t = \frac{A_t}{\Delta_t} L_t^{\alpha_1} \bar{K}_t^{\alpha_2} \left(O_t + X_t \right)^{1-\alpha_1-\alpha_2}, \tag{64}$$

the rule followed by the monetary authority,

$$\frac{R_t}{\bar{R}} = e^{r_t} \left(\frac{R_{t-1}}{\bar{R}} \right)^{\phi_R} \left(\frac{\Pi_t}{\bar{\Pi}} \right)^{\phi_\pi} \left(\frac{p_{ot}}{p_{ot-1}} \right)^{\phi_o}, \tag{65}$$

and the global resource constraint,

$$C_t = Y_t - p_{ot} \left(O_t + X_t \right). \tag{66}$$

We assume throughout that OPEC can commit to the optimal policy rule that brings about the equilibrium which maximizes expression (54) above. Furthermore, we restrict our attention to Markovian stochastic processes for all exogenous variables, and to optimal decision rules which are time-invariant functions of the state of the economy.

2.5 Flexible Price Benchmarks

We begin by characterizing the equilibrium allocation in two benchmark scenarios which we will use later to evaluate alternative monetary strategies. One is the *natural* allocation, which corresponds to the equilibrium that would obtain if all prices were fully flexible. And the other is the *efficient* allocation, which we define as the allocation that would obtain if prices were fully flexible and there was perfect competition in oil production.

We make use of the following relation for equilibrium labor which holds regardless of the behavior of the oil sector. Substituting (22), (39), (40), and (42) into (50), we can solve for equilibrium labor as a function of marginal cost and relative price dispersion in the US:

$$L_t = \left[\frac{\alpha_1 mc_t \Delta_t}{1 - (1 - \alpha_1 - \alpha_2) mc_t \Delta_t} \right]^{\frac{1}{1+\psi}}. \tag{67}$$

2.5.1 Efficiency: perfect competition in oil and flexible prices

The efficient allocation (denoted by the superscript "e") is the one which would obtain under perfect competition in oil production and fully flexible prices.[10]

Will full price flexibility (attained by setting $\theta = 0$) all firms charge the same price and hence in the symmetric equilibrium there is no price dispersion,

$$\Delta_t^e = 1. \tag{68}$$

Moreover, in this case marginal costs are constant and equal to the inverse of the optimal markup of final goods firms (related to the elasticity of substitution among final goods)

$$mc_t^e = \mu^{-1} = \frac{\epsilon - 1}{\epsilon}.$$

With these substitutions, equation (67) reduces to

$$L_t^e = \left[\frac{\alpha_1}{\mu - (1 - \alpha_1 - \alpha_2)} \right]^{\frac{1}{1+\psi}} \equiv \bar{L}, \tag{69}$$

which implies that equilibrium labor is constant, unaffected by shocks. At the same time, equation (39) becomes

$$p_{ot}^e O_{dt}^e = (1 - \alpha_1 - \alpha_2) \mu^{-1} Y_t^e. \tag{70}$$

If, in addition, the dominant oil exporter operated as a perfect competitor, the real price of oil would be equal to its marginal cost,[11]

$$p_{ot}^e = mc_{ot} = Z_t^{-1}, \tag{71}$$

which is exogenously given. We can establish the following

[10] Without loss of generality, we keep in the definition the static distorion due to monopolistic competition in the oil importing country.

[11] Since our focus is on OPEC, we rule out the corner solution in which the collective supply of the more efficient fraction of the competitive fringe is sufficient to meet all demand and price OPEC out of the market.

Proposition 1 *With exogenous or competitive oil prices and full price flexibility, a shock to the oil price (or to the marginal cost of oil production) is equivalent to a total factor productivity shock.*

Proof. Equations (71) and (70) combined with (42) imply

$$Y_t^e = \left[A_t Z_t^{1-\alpha_1-\alpha_2}\right]^{\frac{1}{\alpha_1+\alpha_2}} \bar{L}^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \bar{K}^{\frac{\alpha_2}{\alpha_1+\alpha_2}} \left[(1-\alpha_1-\alpha_2)\mu^{-1}\right]^{\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} \tag{72}$$

Labor and real marginal costs are constant, and all other real endogenous variables of the oil importer (w_t, r_t, C_t, and O_{dt}) can be expressed in terms of Y_t^e. ■

In other words, apart from a possible scaling down by the share of oil in output, an oil price shock (a change in Z_t) affects the efficient level of output and all real variables in the same way as a TFP shock (a change in A_t).

Corollary 2 *With an exogenous or competitive oil sector any movements in the oil price caused by real shocks represent shifts in the efficient level of output.*

2.5.2 Replicating the efficient allocation under sticky prices

The above corollary suggests that one thing that monetary policy should not attempt is to "neutralize" shifts in competitively set (or exogenous) oil prices. We can show that in a scenario with sticky goods prices and an exogenous or competitive oil price, monetary policy can replicate the efficient equilibrium by targeting inflation alone, as stated in the following

Proposition 3 *If the oil price is exogenous or competitive and there is no price dispersion initially, then the optimal monetary policy is full price stability.*

Proof. See Appendix 3 ■

In other words, with an exogenous or competitive oil price, there is a "divine coincidence" of monetary policy objectives in the sense of Blanchard and Galí (2006): stabilizing inflation will automatically stabilize the distance between output and its efficient level.

The intuition for this result is straightforward: with a competitive or exogenous oil price, there is only one source of distortion in the economy – the one associated with nominal rigidity. A policy of full price stability eliminates this distortion and replicates the efficient allocation.

The following sections show how this result can be overturned with a dominant oil supplier.

2.5.3 Natural allocation: market power in oil and flexible prices

The natural allocation (denoted by the superscript "n") is defined as the one which would obtain if all prices were fully flexible. In this case, it is straightforward to show that equilibrium labor supply is constant and given by equation

(69). We can use this fact to derive a relationship between the oil price and the demand for oil that obtains under flexible prices,

$$p_{ot}^{n}=(1-\alpha_1-\alpha_2)\mu^{-1}A_t\bar{L}^{\alpha_1}\bar{K}^{\alpha_2}\left(O_{dt}^{n}\right)^{-\alpha_1-\alpha_2}. \tag{73}$$

Consecutive substitution of (55) into (51) and the resulting expression into the equation above yields an oil demand curve which relates directly the natural price of oil to the demand for OPEC's output independently of any other endogenous variables. This greatly simplifies the problem of OPEC (54) since now the only relevant constraint for the maximization of profits is a single demand curve (75). Hence, OPEC solves

$$\max_{O_t^n}\ E_0\sum_{t=0}^{\infty}\beta^t\log[p_{ot}^{n}O_t^n-O_t^n/Z_t] \tag{74}$$

s.t.

$$p_{ot}^{n}=(1-\alpha_1-\alpha_2)\mu^{-1}A_t\bar{L}^{\alpha_1}\bar{K}^{\alpha_2}\left(O_t^n+\Omega_t p_{ot}^{n}Z_t\right)^{-\alpha_1-\alpha_2} \tag{75}$$

The solution to this problem implies that the price of oil is a time-varying markup ν_t^n over marginal cost mc_{ot},

$$p_{ot}^{n}=\nu_t^n mc_{ot}, \tag{76}$$

where marginal cost is given by

$$mc_{ot}=Z_t^{-1}=p_{ot}^{e} \tag{77}$$

while the optimal markup is inversely related to the (absolute) price elasticity of demand for OPEC's oil:

$$\nu_t^n=\frac{\left|\varepsilon_t^{O^n,\,p_o^n}\right|}{\left|\varepsilon_t^{O^n,\,p_o^n}\right|-1}. \tag{78}$$

The latter can be derived from constraint (75) as

$$\left|\varepsilon_t^{O^n,\,p_o^n}\right|\equiv\left|\frac{\partial O_t^n}{\partial p_{ot}^n}\frac{p_{ot}^n}{O_t^n}\right|=\frac{1}{\eta s_t^n}-1, \tag{79}$$

where $\eta\equiv\frac{\alpha_1+\alpha_2}{1+\alpha_1+\alpha_2}$, and $s_t^n=\frac{O_t^n}{O_t^n+X_t^n}$ is the natural market share of OPEC.

Since $(\alpha_1+\alpha_2)\in(0,\ 1)$ implies $\eta\in(0,\ 0.5)$, and given that $s_t^n\in[0,\ 1]$, we have $\eta s_t^n\in(0,\ 0.5)$ and therefore $\left|\varepsilon_t^{O,\,po}\right|\in(1,\ +\infty)$. This implies that the profit-maximizing dominant firm produces always on the elastic segment of its effective demand curve and that the oil price markup is positive ($\nu_t^n>1$).

Moreover, from (79) we see that the (absolute) price elasticity of demand for OPEC's oil is a decreasing function of OPEC's market share. Hence, a negative shock to the supply of the competitive fringe which increases OPEC's market share, makes the demand for OPEC's oil less price-elastic, raising the optimal markup charged by OPEC.

Substituting (79) into (78) we can obtain a direct relationship between the optimal oil price markup and the market share of the dominant oil exporter,

$$\nu_t^n = \frac{\eta s_t^n - 1}{2\eta s_t^n - 1}, \tag{80}$$

which in a first-order approximation around the steady state becomes

$$\hat{\nu}_t^n = \frac{\eta}{(2\eta\bar{s} - 1)^2}\hat{s}_t^n.$$

This implies that, up to a first-order approximation, the oil price markup co-moves with OPEC's market share,

$$corr(\nu_t^n,\ s_t^n) \approx 1. \tag{81}$$

2.5.4 Full Monopoly in Oil Production

It is informative to consider the special case of a single oil supplier with full monopoly power (corresponding to $\Omega_t = 0$ and $s_t^n = 1$). The solution (denoted by the superscript "m") implies:

$$O_t^m = \left[(1-\alpha_1-\alpha_2)^2\mu^{-1}A_t Z_t \bar{L}^{\alpha_1}\bar{K}^{\alpha_2}\right]^{\frac{1}{\alpha_1+\alpha_2}}, \tag{82}$$

$$p_{ot}^m = \frac{1}{Z_t\left[1-\alpha_1-\alpha_2\right]} = \nu^m p_{ot}^e \tag{83}$$

The price of oil is a constant markup over marginal cost, where the optimal markup $\nu^m = [1-\alpha_1-\alpha_2]^{-1}$ is the inverse of the elasticity of oil in final goods production. For instance, if $1-\alpha_1-\alpha_2 = 0.05$, the optimal markup ν^m would be 20!

The intuition for this result is straightforward: with $s_t^n = 1$ the price elasticity of demand for the monopolist's oil (79) reduces to

$$\left|\varepsilon_t^{O^m,\ p_o^m}\right| = \left|\frac{\partial O_t^m}{\partial p_{ot}^m}\frac{p_{ot}^m}{O_t^m}\right| = \frac{1}{\alpha_1+\alpha_2} = \frac{1}{1-(1-\alpha_1-\alpha_2)}. \tag{84}$$

In words, with a single oil monopolist the (absolute) price elasticity of oil demand is positively related to the elasticity of oil in production. Therefore, a small share of oil in output implies that oil demand is quite insensitive to the price, which allows the monopolist to charge a high markup.

Finally, notice that the existence of a competitive fringe greatly reduces OPEC's optimal markup. For example, if in steady-state the supply of the competitive fringe is roughly equal to that of OPEC ($O_t^n = X_t^n$), OPEC's optimal markup reduces to a level which is an order of magnitude lower than the full monopoly markup,

$$s_t^n = 0.5 \Longrightarrow \nu^n = 1 + \frac{\alpha_1+\alpha_2}{2} = 1.475 << \nu^m = 20. \tag{85}$$

2.5.5 The natural output gap

We call "natural output gap" (denoted $\tilde{Y}_t^n$) the distance between the natural level of output, Y_t^n, and its efficient counterpart, Y_t^e. It is straightforward to show that this distance is a function only of the natural oil price gap (p_{ot}^n/p_{ot}^e), which from (76) and (77) is equal to the oil price markup in the natural allocation,

$$\tilde{Y}_t^n \equiv Y_t^n/Y_t^e = (p_{ot}^n/p_{ot}^e)^{-\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} = (\nu_t^n)^{-\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} . \tag{86}$$

Since we have seen in (78) that with a dominant oil supplier the oil price markup is always greater than one, the natural equilibrium is characterized by underproduction in the US, related to an inefficiently low oil supply by OPEC. Moreover, contrary to the polar cases of perfect competition or full monopoly power in oil, in the intermediate case with a dominant firm, the oil price markup fluctuates in response to all real shocks. And while these fluctuations are optimal responses from the point of view of OPEC, they are distortionary from the point of view of the US economy. Therefore, if US monetary policy can affect the actual evolution of output, it would make sense to counter, at least to some extent, fluctuations in the oil price markup, in addition to targeting inflation.

2.6 Equilibrium with Sticky Prices

Given a certain degree of price stickiness, monetary policy can affect the real economy in the short run. In particular, it can affect US output, and indirectly the demand for oil and its price.

The equilibrium with sticky prices and a dominant oil supplier is defined by a set of time-invariant decision rules for the endogenous variables as functions of the state and the shocks observed in the beginning of each period, which satisfy constraints (55) - (66) and which solve the dominant oil supplier's problem in (54).

We derive an expression for the welfare-relevant output gap, $\tilde{Y}$, defined as the distance between actual output and its efficient level given by (72). As shown in Appendix 2, the output gap is related to real marginal costs — a standard result in the New Keynesian literature — but in our model also to the oil price markup ν_t^n. Thus, up to a first-order approximation, fluctuations in the output gap are related to shifts in these two variables:

$$\tilde{y}_t = \kappa_{mc}\hat{mc}_t - \kappa_\nu \hat{\nu}_t^n, \tag{87}$$

where κ_{mc} and κ_ν are parameters defined in the Appendix, $\hat{mc}_t$ are real marginal costs in the final goods sector, and $\hat{\nu}_t^n = \hat{p}_{ot} - \hat{p}_{ot}^e = \hat{p}_{ot} + \hat{z}_t$ is the oil price markup, both in log-deviations from steady-state.

Proposition 4 *In the presence of a dominant oil supplier, optimal monetary policy would seek to strike a balance between stabilizing inflation and stabilizing the output gap.*

From equation (87) we see that a policy aimed at full price stability would set $\hat{mc}_t$ equal to zero and would thus stabilize the gap between actual output and its natural level. Yet this would not stabilize fully the welfare-relevant output gap, since in response to all real shocks OPEC induces inefficient fluctuations in the oil price markup $\hat{v}_t$ independently of any price stickiness. These fluctuations are reflected in a time-varying wedge between the natural and the efficient level of output, as shown in (86).

The above result breaks the "divine coincidence" of monetary policy objectives and provides a rationale for the central bank to mitigate to a certain extent inefficient output gap fluctuations by tolerating some deviation from full price stability. Notice that the source of inefficiency is endogenous here, as it is an outcome of the profit-maximizing behavior of OPEC.

2.7 Calibration

We calibrate our model so that it replicates some basic facts about the US economy and OPEC. Table 1 shows the parameters used in the baseline calibration. The quarterly discount factor corresponds to an average real interest rate of 3% per annum. Utility is logarithmic in consumption and we assume a unit Frisch elasticity of labor supply. We set the elasticity of labor in production equal to 0.63 and the elasticity of capital to 0.32, consistent with measures of the average labor and capital shares in output. This implies an elasticity of oil of 0.05 and an oil share of $0.05/\mu \approx 0.04$, which roughly corresponds to the value share of oil consumption in US GDP. The Calvo price adjustment parameter is set equal to 0.75, implying an average price duration of one year. The elasticity of substitution among final goods is assumed to be 7.66 corresponding to a steady-state price markup of 15%. And the mean of the total capacity of non-OPEC producers is set to match the average market share of OPEC of around 42%.

We choose the baseline parameters of the monetary policy rule as follows. We set the target inflation rate equal to zero, consistent with the optimal long-run inflation in our model.[12] The short-run reaction coefficient on inflation is set to 0.4, while the interest rate smoothing parameter is set to 0.8, implying a long-run inflation coefficient of 2. These values are similar to the estimates by Clarida, Gali and Gertler (2000) for the Volcker-Greenspan period. The baseline short-run coefficient on oil price inflation is set equal to zero.

There are three real and one nominal exogenous variables in our model. For US total factor productivity we assume an AR(1) process with standard deviation of the innovation of 0.007 and an autoregressive parameter of 0.95, similar to those calibrated by Prescott (1986) and Cooley (1997). With these values we are able to match the standard deviation and persistence of US GDP growth from 1973:I to 2007:I. Similarly, the processes for oil technology and the capacity of non-OPEC producers are parametrized to match the volatility of the oil

[12] More on this in the following section.

price (about 20 times more volatile than US GDP), its autoregressive coefficient (0.97), as well as the relative volatility of OPEC versus non-OPEC output (the former is five times more volatile) over the same period.[13] Finally, the interest rate shock is assumed to be *i.i.d.* with standard deviation corresponding to a 25 basis points disturbance of the interest rate rule (10).

In the following section we study the steady-state properties of the model and perform comparative statics exercises varying some of the above parameters. And in section 5 we test the sensitivity of the dynamic properties of the model with respect to the elasticity of oil in production, as well as to different parametrizations of the monetary policy rule.

Structural parameters			Calibrated to match
Quarterly discount factor	β	0.9926	Aver. annual real rate 3%
Elasticity of output wrt labor	α_1	0.63	Aver. labor income share
Elasticity of output wrt capital	α_2	0.32	Aver. capital income share
Elasticity of output wrt. oil		0.05	Oil consumption in GDP
Price adjustment probability	θ	0.75	Aver. price duration 1 yr
Price elasticity of substitution	ϵ	7.66	Aver. markup 15%
Mean of non-OPEC capacity	$\bar{\Omega}$	0.0093	OPEC market share 42%
Inv. Frisch labor supply elast.	ψ	1	Unit elasticity
Monetary policy			
Long run inflation target	$\bar{\Pi}$	1	Optimal target
Interest rate smoothing coeff.	ϕ_R	0.8	Estimated
Inflation reaction coefficient	ϕ_π	0.4	Estimated
Oil price reaction coefficient	ϕ_{po}	0	
Shock processes			
Std of US TFP shock	σ_a	0.007	US GDP volatility
Persistence of US TFP shock	ρ_a	0.95	US GDP persistence
Std of oil tech. shock	σ_z	0.12	Oil price volat. wrt GDP
Persistence of oil tech. shock	ρ_z	0.95	Oil price persistence
Std of non-OPEC capacity	σ_ω	0.10	Volat. of non-OPEC
Persist. of non-OPEC capacity	ρ_ω	0.975	relative to OPEC supply
Std dev of int. rate innovation	σ_r	0.001	Interest rate shock 25 bp

Table 1. Baseline calibration

3 Steady State and Comparative Statics

We focus our attention on the steady-state with zero inflation. The reason is that for an empirically plausible range of values for the reaction coefficients of the monetary policy rule, the optimal long-run rate of inflation in our model (from the point of view of the US consumer) is essentially zero.

[13] Quarterly data on OPEC and non-OPEC oil output are taken from EIA (2007), and on US GDP from FRED II. Actual and model-generated data are made comparable by taking growth rates and then subtracting the mean growth rate for each variable. Volatility is measured as the standard deviation of the demeaned growth rate series.

The zero inflation steady-state is characterized by an inefficiently low oil supply by OPEC[14], a positive oil price markup, and underproduction of final goods in the US. In particular, under our baseline calibration OPEC produces only 45% of the amount of oil that it would produce if it operated as a competitive firm. This allows it to charge a markup of around 36% over marginal cost, and make a positive profit of around 0.5% of US output (or around $65 billion per annum based on nominal US GDP in 2006). At the same time, imperfect competition in the oil market opens a steady-state output gap in the US of 1.6% ($208 billion per annum).

Figures 3 and 4 show two comparative statics exercises. Figure 3 illustrates the sensitivity of the steady-state to the availability of oil outside OPEC. In the face of a 50% reduction of the capacity of competitive oil producers with respect to the baseline, OPEC's output increases only by 10%. The market share of OPEC increases, and by (80) the oil price markup jumps from 35% to 75% over OPEC's marginal cost. This widens the US output gap to 3%, while doubling OPEC's profit as a share of output. The relationship however is highly nonlinear and a further reduction of the capacity of oil producers outside OPEC results in a much more dramatic increase in the equilibrium price of oil and a larger output loss in the US.

Figure 4 shows the sensitivity of the results to the elasticity of oil in output. Keeping the capacity of non-OPEC producers constant, an increase of the oil elasticity raises the market share of OPEC. As a result, the oil price jumps to 57% over marginal cost and the US output gap widens to 5%.

4 Dynamic Properties of the Model

We solve the model numerically by first-order Taylor approximation of the decision rules around the deterministic steady-state with zero inflation (following Blanchard and Kahn (1980)).[15] This section reports some of the more interesting dynamic features of the economy under our preferred calibration.

Figures 5, 7, 9 and 11 show the impulse-response functions for several variables of interest. The signs of the shocks are chosen so that all impulses result in an increase in the oil price on impact. The figures plot the efficient allocation (denoted by the superscript "e"); the natural allocation (denoted by "n"; it coincides with the actual evolution under a policy of full price stability); and the actual evolution of the relevant variables with nominal rigidity and under the benchmark policy rule.

To help clarify the intuition, the bottom-right panel of the figures shows three output gap measures: the actual (or welfare-relevant output gap, denoted by

[14]This result ignores any longer term costs of oil associated with environmental pollution and global warming.

[15]Solving the model by second-order approximation yields virtually identical impulse-response functions.

$\tilde{Y}$), the natural output gap (denoted by $\tilde{Y}^n$), and the "sticky price output gap" (denoted by $\tilde{Y}^s$), defined as the distance between the actual and the natural level of output.

4.1 US technology shock

We begin with a typical (one-standard-deviation) positive shock to US total factor productivity in figure 5. Consider first the efficient allocation. As is standard in RBC models, the efficient level of output rises (in our case by 0.74%). Since OPEC acts competitively and there is no change in the marginal cost of oil production, the oil price remains constant. Because there is no change in the price, the supply of the fringe stays fixed as well. With OPEC as the marginal oil producer, all of the additional oil demand is met by a rise in OPEC's supply, which raises OPEC's market share.

Now let's turn to the natural evolution and compare it to the efficient one. In response to the positive TFP shock, dominant OPEC raises its oil supply, while engineering a slight increase in the oil price markup.[16] This is a consequence of profit maximization subject to downward-sloping demand: since OPEC's profit is the product of the oil price markup and oil output, in the face of stronger US demand for oil due to oil's enhanced productivity, it is optimal to increase both profit factors. As figure 5 shows, this requires that OPEC increase its supply by a slightly smaller fraction of steady-state output than if it operated as a perfect competitor.[17]

Due to the oil price rise, the supply of non-OPEC increases as well, albeit by less than OPEC. OPEC's market share rises, consistent with the increase in the oil price markup as per equations (80) and (81). Natural output in the US increases by slightly less than the efficient amount because of the inefficient response of natural oil supply. Quantitatively, however, the natural output gap moves very little in response to a US technology shock. This suggests that, with respect to US TFP shocks, a policy aimed at full price stability would almost stabilize the output gap.

Finally, consider the actual allocation with nominal rigidity and given the benchmark policy rule (10). Inflation falls by around 30 basis points (annualized), while output increases by 0.61% — less than the efficient increase. As it turns out, most of the inefficiency in response to the US TFP shock stems from the suboptimality of the benchmark policy rule. This can be seen from the bottom-right panel, in which nearly all of the 13 basis points fall (that is,

[16] The latter can be seen as the difference between the natural and the efficient response of the oil price.

[17] Figure 6 illustrates this in the case of linear demand. If OPEC operated as a perfect competitor, an increase in demand would move it from point A to point A' where marginal cost crosses the new oil demand schedule. The oil price remains unchanged and all adjustment falls on oil supply. Since instead OPEC is a profit-maximizing monopolist, marginal revenue shifts out by less than the oil demand schedule. As a result, both oil output and the oil price rise as OPEC moves from point B to point B'.

widening) of the output gap induced by the shock is attributable to the fall of the "sticky price output gap" ($\tilde{Y}^s$). Hence, there is almost no tradeoff between inflation and output gap stabilization. Compared to the benchmark Taylor-type rule, a positive technology shock calls for a more aggressive interest rate *reduction* even if the shock is associated with a slightly rising oil price.

4.2 Oil technology shock

We next discuss the responses to a one-standard-deviation negative shock to oil productivity shown in figure 7. Again, we focus in turn on the evolution of the efficient, the natural, and the actual allocations.

First, because a negative oil technology shock is a positive marginal cost shock for the oil industry, the efficient level of oil supply falls while the efficient oil price rises (by 12%). Since oil is an intermediate input, the efficiency of final goods production is also affected, so that the first-best level of output declines by 0.65%. The supply of the fringe remains constant because the oil price rise is entirely offset by the increase in the marginal cost of oil production. As a result, OPEC's share declines in response to the shock.

In the natural equilibrium, since marginal revenue is steeper than the demand curve, OPEC's oil price markup decreases, meaning that the natural oil price rise (around 9%) is less than the efficient increase (of 12%).[18] Similarly, the fall in OPEC's output (as a fraction of steady-state) is less than the efficient decline. Because of the decrease of the oil price markup, non-OPEC supply falls by around 3%, while OPEC's market share declines by around 3 percentage points, shadowing the movement of the oil price markup.

Actual US output falls by around 0.4%, which is less than the efficient decline of 0.65%.[19] As a result, the rise in inflation by 20 basis points is accompanied by an increase (that is, narrowing) of the output gap by around 25 basis points. In contrast to the previous shock, however, this time much of the output gap movement is "natural" in the sense that it is attributed more to the temporary fall in the oil price markup than to sticky prices.

The part of the output gap due to sticky prices can be stabilized better by raising the nominal rate more aggressively than the benchmark rule (10) prescribes. In fact, a policy of full price stability would bring the response of the output gap down to that of the natural output gap (a 19 basis points rise, instead of 25), which is unambiguously welfare-improving compared to the benchmark rule. But, clearly, a policy of full price stability is not optimal either, as it is not able to fully stabilize the output gap, and in general results

[18] Figure 8 illustrates this in the case of linear demand.

[19] This output response is in the ballpark of empirical estimates of the response of US GDP to an "oil price shock"; admittedly, uncertainty about this empirical response is an order-of-magnitude large: according to Bernanke et al. (2004) and IMF(2005) a 10% increase in the oil price leads to a 0.10% to 0.20% drop in US GDP after 1 to 2 years. On the other extreme, Rotemberg and Woodford (1997) and Finn (2000) argue that the effect is as large as a 2.5% drop in GDP after 5 to 7 quarters.

in excessive output gap variation. In order to stabilize the output gap more, the central bank would have to allow some amount of deflation. In other words, the optimal rule would seek to strike a balance between stabilizing prices and stabilizing the output gap. From the point of view of rule (10), in response to a negative oil technology shock which raises the oil price, the central bank should *raise* the nominal rate by more than what the benchmark rule prescribes (but not by so much as to cause excessive deflation).

4.3 Fringe capacity shock

In third place we analyze the effects of a one-standard-deviation negative shock to the total capacity of competitive fringe producers.[20]

First notice in figure 9 that this shock has no effect on the efficient oil price or on the first-best level of output (the latter can be seen also in expression (72) in which the fringe shock does not appear). The reason is that, unlike the oil technology disturbance, the fringe shock does not affect the efficiency of oil production. The latter in turn is related to the fact that in the efficient equilibrium, and for the allowed size of oil demand and fringe shocks, the aggregate oil supply curve is flat at the marginal cost of OPEC. Since OPEC can supply any amount of oil at that price, shocks to fringe capacity are of no relevance for the marginal cost of oil production and as a consequence do not affect the efficient level of output.

Turning to the natural allocation, a negative fringe shock decreases non-OPEC supply by 7.3% and raises OPEC's market share by around 2.6 percentage points. By (79) the effective demand for OPEC oil is less price-elastic, which implies that the profit-maximizing oil price is higher by around 2.7%. OPEC's output increases by less than the decrease in non-OPEC supply, and as a consequence total oil production declines. The resulting drop in US output (by around 0.15%), coupled with the constancy of the efficient level of output, translates one-for-one in a fall (that is, widening) of the natural output gap by 15 basis points.

The actual allocation for this shock almost coincides with the natural one. The output gap fall is by 14 basis points and it is accompanied by a rise in inflation by 3 basis points. Importantly, virtually all of the output gap fall is due to imperfect competition in the oil sector and as such cannot be stabilized through a policy of price stability. In fact, any attempt to stabilize the output gap in this case would come at the cost of increasing inflation. Hence, with respect to this shock, optimal monetary policy would involve a traditional trade-off between inflation and output gap stabilization. With respect to the benchmark rule, the central bank should either *raise* or *lower* the nominal interest rate, depending on the relative benefit of inflation versus output gap stabilization.

[20] Alternatively, one could think of the negative fringe shock as a positive demand shock from the rest of the world (e.g. China), where demand is postulated to decrease linearly in the price.

Finally, notice in passing that this shock creates a negative conditional correlation between OPEC and non-OPEC oil supply. This negative correlation features importantly in the data throughout the 1980s when non-OPEC oil production (especially that of UK, Norway, Russia and Mexico) took off, while OPEC's output was essentially halved (see figure 10).

4.4 Monetary policy shock

Finally, we illustrate the monetary transmission mechanism by tracing out the effects of a monetary policy shock in figure 11. The efficient and the natural allocations are of course unaffected by this type of shock.

In terms of the actual allocation, in response to an unexpected 25 basic points interest rate cut, US output (+0.25%) and inflation both rise (+45 bp) as is standard in the New Keynesian model. OPEC responds to the rise in demand by raising its output (+1.3%) while engineering an increase in the oil price markup (+0.2%). The supply of the competitive fringe increases by the same proportion as the oil price markup. This is less than OPEC's supply rise and OPEC's share increases, in line with the oil price markup rise. Since the efficient and the natural levels of output remain constant, the shock results in an inefficient rise (narrowing) of the output gap by 25 bp, all of which is attributable to sticky prices. Monetary policy in this model has a strong influence on the actual evolution of output and prices and can be used as an effective tool to offset the real disturbances causing inefficient fluctuations in welfare-relevant variables.

4.5 Summary and policy implications

Table 2 summarizes the conditional correlation of the oil price with US output, the output gap, inflation and the oil price markup (or OPEC's share), induced by each of the four shocks under the benchmark monetary policy rule. In addition, the last column of the table sums up the policy implications of each type of shock, relative to the prescription of the benchmark policy rule.

The table shows that the oil price could be positively or negatively correlated with the output gap and inflation depending on the source of the shock. A somewhat surprising finding, perhaps, is that conditional on an oil technology shock, the oil price is positively correlated with the output gap (as mentioned earlier, the reason is that conditional on this shock, the oil price is negatively related to the oil price markup). In contrast, the oil price is negatively correlated with the output gap if the shock is due to an unexpected change in non-OPEC capacity.

Related to the above, the policy implications of an oil price change depend crucially on the underlying source of the shock. In particular, an oil price increase due to a negative oil technology shock calls for a somewhat *higher* interest rate vis-a-vis the benchmark, since this type of shock lowers the efficient level of output while imperfect competition in the oil market (as well as price stickiness) prevent actual output from falling sufficiently. As we saw in section 4.2, a typical negative oil technology shock which raises the oil price by 9% results in a 3% decrease in the oil price markup. Because of the relatively small share of oil in output, this translates into a 25 basis points increase in the output gap (and a 20 bp rise in inflation). If the central bank were to offset completely the effect of the shock on the output gap, it would have to raise the nominal rate by roughly 25 basis points above the benchmark policy rule.

In contrast, an oil price increase associated with a negative fringe shock may well require a *lower* interest rate with respect to the benchmark. This is because the efficient level of output remains unaffected, while actual output falls as OPEC uses the opportunity to raise the oil price markup. In particular, a typical fringe shock raises the oil price markup by 3%, which translates into a 20 basis points decrease in the output gap. Therefore, if the central bank wants to offset completely the effect of the shock on the output gap, it would have to lower the interest rate by around 20 basis points relative to the benchmark rule. Of course, in both scenarios, there is no reason why the central bank should want to completely insulate the output gap from the shock, since that would generate below target inflation (deflation) in the former case, and above target inflation in the latter.

Lastly, if the oil price rise is caused by a rise in technology (and oil productivity) in the US, the interest rate should be set *lower* than the benchmark rule for a reason independent of the oil price movement. Namely, the interest rate smoothing of rule (10) prevents it from offsetting the output gap and inflation fall due to the shock in the presence of nominal rigidities. Unlike the previous two disturbances, for this shock the tradeoff between inflation and output gap stabilization is quantitatively small.

Shock		Cond. correlation Y	$\tilde{Y}$	Π	υ	Desirable deviation from benchmark rule (10) in response to an oil price rise
Z	p_o^Z	$-$	$+$	$+$	$-$	$R\uparrow$ to stabilize $\tilde{Y}$, tradeoff for deflation
Ω	p_o^Ω	$-$	$-$	$+$	$+$	$R\downarrow\uparrow$, traditional $\Pi-\tilde{Y}$ tradeoff
A	p_o^A	$+$	$-$	$-$	$+$	$R\downarrow$ to stabilize Π, virtually no tradeoff
R	p_o^R	$+$	$+$	$+$	$+$	

Table 2. Oil price correlations and policy implications conditional on shock

4.6 A note on Taylor-type reaction to the oil price

Taylor (1993)-type rules are often advocated as useful guidelines for policy on the basis of their simplicity and good performance (in terms of implied welfare loss) in the standard sticky price model. In its simplest form, in the context of the New Keynesian model, a Taylor rule prescribes that the central bank should adjust sufficiently the interest rate in response to variations in inflation and the welfare-relevant output gap. In fact, as already discussed, in the standard New

Keynesian model stabilizing inflation is equivalent to stabilizing the output gap and hence the latter term can be dropped from the rule. But in the absence of "divine coincidence" of monetary policy objectives, as in this model, the presence of the output gap in the rule is justified as it would result in superior performance in general compared to a rule which reacts to inflation only.

Unlike inflation, though, the output gap is an unobservable variable, making a rule which reacts to it less useful as a policy guide. In our context, it may be interesting to know whether there is an observable variable, perhaps the oil price or its change, which is a good substitute for the output gap. Indeed, to the extent that some inflation-targeting central banks target not "core" but "headline" inflation, which includes the price of energy, a Taylor type rule would implicitly react to energy price changes proportionately to the share of energy in CPI. What can we say about the advisability of a Taylor rule reacting to the oil price on the basis of our findings?

From our discussion in the previous section it is already clear that a mechanical Taylor-type reaction to the oil price regardless of the source of the shock is not likely to be very useful, and might even be harmful. The reason is that, as witnessed in table 2, the correlation of the oil price with the output gap can be either positive or negative conditional on the type of the shock. As a result, the unconditional correlation between the oil price and the output gap can be quite weak (-0.11 under our benchmark calibration).

As shown in section 2.5.5, it is instead the oil price *markup* which enters unambiguously in the expression for the output gap. And while the oil price markup may be difficult to come by in practice because of the lack of reliable estimates of OPEC's marginal costs, according to our model it should be highly positively correlated with OPEC's market share, a variable which is more directly observable. In this sense, rather than removing energy prices from the "headline" consumer price index to obtain an index of "core" inflation, our analysis suggests treating the oil price markup (or OPEC's market share) as an independent target variable.

4.7 Variance decomposition

To assess the relative importance of the four sources of fluctuations in our model, in table 3 we show the asymptotic variance decomposition for several key variables, along with their unconditional standard deviations. Clearly, these statistics are sensitive to our baseline calibration of the shock processes.

In particular, under our baseline calibration, US technology shocks account for around 40% of the volatility of inflation, 68% of the volatility of output, but only 3% of the volatility of the welfare-relevant output gap. Oil technology shocks are responsible for around 16% of the volatility of inflation, 26% of the volatility of output, and as much as 44% of the volatility of the output gap. Fringe shocks contribute only 1% of the volatility of inflation and 5% of the volatility of output, but as much as 44% of the volatility of the output gap. And monetary policy shocks are responsible for 44% of the volatility of inflation, 1% of the volatility of output, and 8% of the volatility of the output gap.

Not surprisingly, US output, inflation and the interest rate can be explained to a large extent by the US-originating technology and monetary policy shocks. Still, as much as 31% of US output variance and 17% of US inflation volatility can be accounted for by the combined contribution of oil technology and fringe shocks. Even more importantly, these two shocks together contribute close to 89% of the variance in the welfare-relevant output gap. Since these are precisely the shocks that make monetary policy interesting (in the sense of inducing a meaningful policy tradeoff), the fact that they account for much of the output gap and inflation variability confirms that the lack of a policy tradeoff in the standard New Keynesian model is just a coincidence.

Another way of seeing this is by observing that under the benchmark policy rule the bulk of the volatility of the actual output gap (std 93 basic points) is due to fluctuations in the natural output gap (std 81 bp). Indeed, the correlation between these two output gap measures is around 0.95. In contrast, the correlation between the natural output gap and the sticky price output gap (std 29 bp) is +0.26. In other words, monetary regime (10) which targets only inflation misses on the opportunity to stabilize the welfare-relevant output gap by countering the fluctuations in the natural output gap (caused by OPEC's time-varying market power), through *opposite* movements in the sticky price output gap (which would entail a negative correlation between the two).

		Std	Variance due to			
			A	Z	Ω	R
US output	Y	0.76	67.50	26.13	5.36	1.01
Output gap	$\tilde{Y}$	0.93	2.94	44.24	44.44	8.38
Natural output gap	$\tilde{Y}^n$	0.81	0.15	44.62	55.23	0.00
Sticky price output gap	$\tilde{Y}^s$	0.29	19.15	7.28	0.24	73.33
Inflation	Π	0.63	39.79	15.72	0.76	43.73
Interest rate	R	0.68	63.20	24.54	1.61	10.65

Table 3. Asymptotic variance decomposition

Note:for inflation and the interest rate "std" is annualized; for US output "std" is the standard deviation (in percentage points) of the quarterly growth rate of output.

5 Sensitivity Analysis

In this section we report the sensitivity of our main findings to the elasticity of oil in production as well as to the monetary policy regime in place.

5.1 The elasticity of oil in production

Expression (87) for the output gap and the expressions for κ_ν and κ_{mc} suggest that the elasticity of oil in final goods production is likely to be an important parameter affecting the model's dynamics. At the same time there is evidence that, at least in the US, this parameter has declined, so that today the oil share in GDP is much smaller than what it used to be three decades ago. To test the extent to which the macroeconomic effects of oil sector shocks depend on this elasticity, we recompute our model with a twice larger oil share, by reducing the share of labor to 0.6 and the share of capital to 0.3.

We find that the impact of oil sector shocks on the US economy approximately doubles with respect to the baseline. In particular, the impact of a typical oil technology shock that raises the oil price by 9% is now a 0.75% drop in US output, a rise (narrowing) of the output gap by 55 basis points, and an increase in inflation by 40 basis points. The impact of a typical fringe shock which increases the oil price by 2.5% is a 0.25% drop in US output, a corresponding fall (widening) of the output gap by 25 basis points and a rise in inflation by 5 basis points.

A larger oil share amplifies the responses of US output and inflation also to monetary policy shocks. The overall effect is that doubling the oil share increases the unconditional volatility of US inflation by around 25%, of output by 41%, and of the output gap by 94% with respect to the baseline. These volatility effects are substantial and point to the possibility that reduced dependence of the US economy on oil may have played an important role in the pronounced decline in US inflation and output volatility since the mid 1980-s (a phenomenon dubbed by some economists as the "Great Moderation", e.g. McConnell and Perez-Quiros (2000)).

5.2 Monetary policy

Table 4 summarizes the stabilization properties of several monetary policy regimes in terms of the implied volatility of US welfare-relevant variables, as well as the impact responses to oil sector shocks (normalized to produce the same 10% increase in the oil price). The alternative monetary policies considered include the benchmark rule (10); full price stability, $\Pi_t = 1$; constant nominal interest rate, $R_t = 1/\beta$; rule (10) with $\phi_\pi = 2$ and without interest-rate smoothing, $\phi_R = 0$; rule (10) with $\phi_\pi = 2$ without smoothing and with (the optimal) oil price reaction $\phi_o = -0.02$; and rule (10) with smoothing and with (a sub-optimal) oil price reaction, $\phi_o = +0.04$. In what follows, we discuss briefly three of these monetary policy regimes.

5.2.1 Constant interest rate policy

How would the economy evolve in the wake of an "oil shock" if the interest rate did not react to any endogenous variable, but instead remained constant? To answer this question we simulate our model under the assumption that the central bank follows a constant nominal interest rate policy.[21]

We find that this rule amplifies dramatically the effects of oil sector shocks on the US economy. In particular, the impact of an oil technology shock which raises the oil price by 10% is an increase in inflation by 2 percentage points — a response which is ten times larger compared to the benchmark policy! US output *increases* by 0.45%, raising (narrowing) the output gap by more than a full percentage point — four times more than the benchmark policy! And in response to a negative fringe capacity shock which raises the oil price by the same 10%, US output (and the output gap) falls by 4% (percentage points for the gap), while inflation *falls* by more than 7 percentage points!

The reason for this very different impact of oil sector shocks is that a constant nominal interest rate policy implies that any movements in expected inflation (including those induced by oil sector developments) translate one-for-one to opposite movements in the ex-ante real interest rate, with the usual consequences for output demand and inflation. For instance, in response to a negative oil technology shock which lowers the efficient level of output, the dominant oil firm optimally commits to reducing future oil supply, inducing a rise in expected inflation. With a constant nominal rate, this lowers the ex-ante real interest rate and stimulates US activity so that instead of falling, output actually increases. The latter boosts temporarily oil demand and mitigates the negative impact of the shock on the dominant oil supplier's profits. Thus, in the absence of active monetary policy, the pursuit of profit-smoothing on behalf of the dominant oil firm comes at the cost of higher volatility in the oil importer. As a result, output volatility increases by 55%, output gap volatility doubles, and inflation volatility increases by a factor of 4.7 with respect to the benchmark policy rule!

5.2.2 Optimal uniform reaction to oil price changes

In section 4.6 we discussed the reasons why a uniform Taylor-type reaction to the oil price is not likely to improve significantly on the benchmark rule. To quantify the extent to which it might help, we compute the optimal uniform reaction to oil price changes, conditional on fixing the long-run reaction coefficient on inflation to its baseline value, and considering the cases with and without interest rate smoothing. To find the optimal coefficient, we approximate the solution of our model to second order and evaluate directly the expected welfare of the US consumer, conditional on the economy starting in the deterministic steady-state.

[21] In our model, the endogeneity of the oil price implies that the Blanchard and Khan (1980) conditions for local determinacy of the solution are satisfied even under a constant interest rate policy.

In the case with interest rate smoothing, the optimal uniform reaction to oil price changes is virtually zero and the welfare gain with respect to the benchmark rule is negligible. We then set the interest rate smoothing parameter to zero while maintaining the same long-run inflation response coefficient. This removes the dependence of the nominal interest rate on oil price and CPI inflation which occurred in the more distant past. We find that in this case, the expected welfare of the US consumer is maximized for a value of the reaction coefficient on the oil price $\phi_o \approx -0.02$.

The particular value for ϕ_o is not very interesting since it is clearly sensitive to the calibration (the relative size of the shocks) of our model. In particular, the optimal reaction should induce more efficient responses to the shocks which fall more strongly on welfare-relevant variables. However, the gain in expected welfare under this rule vis-a-vis the same rule with $\phi_o = 0$ is quite modest — equivalent to a permanent rise in consumption of only 0.02% (or around \$1.8 billion per year based on US consumption expenditure in 2006).

5.2.3 Sub-optimal uniform reaction to oil price changes

If the optimal uniform reaction does not improve significantly on the performance of the benchmark policy, how harmful can a sub-optimal Taylor-type reaction to the oil price be (assuming a plausible response coefficient)? Let us suppose that the monetary authority chooses a contemporaneous reaction coefficient to oil price inflation $\phi_o = 0.04$ keeping all other parameters constant (that is, a long run inflation reaction of 2).

In response to a negative oil technology shock which raises the oil price by 10%, the nominal interest rate increases by around 125 basis points. As a result output falls by 1.3% and inflation falls by 90 basis points. Importantly, US output falls by more than the efficient decrease *widening* the output gap by around 50 basis points (contrary to the output gap *narrowing* by around 25 bp under the benchmark rule). And in response to a negative fringe shock which raises the oil price by 10%, output falls by 1.5% which widens the output gap by 150 basis points (compared to the 50 bp widening under the benchmark rule), at the same time as inflation decreases by around 140 basis points. Therefore, this policy is clearly destabilizing, throwing the economy into an unnecessary recession in response to oil sector shocks which raise significantly the oil price.

	Benchmark	$\Pi_t = 1$	$R_t = \beta^{-1}$	$\phi_R = 0$	$\phi_o = -.02$	$\phi_o = .04$
Unconditional standard deviation						
Output gap	0.93	0.81	1.85	0.83	0.85	1.11
Inflation	0.63	0	2.99	0.43	0.42	1.28
Interest rate	0.68	0.45	0	0.87	0.89	1.70
Impact responses to an oil tech. shock that raises the oil price by 10%						
Output	-0.43	-0.53	0.45	-0.52	-0.36	-1.29
Output gap	0.28	0.21	1.10	0.21	0.36	-0.51
Inflation	0.21	0	2.01	0.11	0.20	-0.90
Interest rate	0.08	0.11	0	0.21	-0.40	1.25
Impact responses to a fringe shock that raises the oil price by 10%						
Output (gap)	-0.49	-0.53	-4.10	-0.54	-0.37	-1.49
Inflation	0.11	0	-7.77	0.03	0.16	-1.39
Interest rate	0.04	0.05	0	0.06	-0.49	1.05

Table 4. Stabilization properties of alternative policy rules

Note: output (%); output gap (percentage points); inflation and interest rate (pp annualized)

To sum up, we find that the monetary policy *regime* in place in the US plays an important role for the behavior of the oil sector and the way in which oil sector shocks are transmitted to the US economy.

6 Conclusion

Killian (2006) argues that the economics profession should move beyond studying the effects of changes in the real price of oil and address the problem of identifying the structural shocks underlying such changes. Only then can economists make the next step of evaluating alternative policies in response to the fundamental shocks. Our model is an attempt in that direction, demonstrating how oil technology and fringe capacity shocks in the oil producing part of the world, combined with monetary policy and TFP shocks in the oil importing region, are transmitted to the price of oil in a world oil market dominated by OPEC. At the same time, and conditional on the monetary policy *regime* in place, each of these shocks affects through different channels the evolution of macroeconomic variables relevant for the oil importer, and as a consequence has distinct policy implications.

Unlike previous studies of the link between oil and the macroeconomy, we model explicitly OPEC as a dominant oil supplier with a fringe of competitive oil producers. This implies that, in equilibrium, the supply of oil fluctuates around an inefficiently low level, reflected in a positive oil price markup and a negative output gap in the US. Importantly, shocks in this environment induce inefficient variation of the oil price markup, and create a meaningful tradeoff between inflation and output gap stabilization — a feature which many central bankers perceive as realistic, but which is absent from the standard monetary policy model.

We are aware that by assuming a frictionless labor market we may be understating the efficiency costs of oil sector shocks. Moreover, our analysis ignores several potentially important aspects of the oil industry: the fact that oil is a storable commodity, which is actively traded on futures markets, and the long gestation lags in adding productive capacity, to name a few. By making oil supply less responsive in the short-run, the latter in particular may be relevant for explaining the puzzlingly high volatility of the oil price relative to oil output. At the same time, we may be omitting other important shocks, for example precautionary demand shifts due to fears about future oil availability (Killian, 2006). We must leave for future research the analysis of some of these issues in an appropriately modified framework.

7 Appendix

7.1 First order conditions of OPEC's problem

$$
\begin{aligned}
0 &= 1/O_t - (\lambda_{1t} + \lambda_{7t})p_{ot} + \lambda_{9t}\left(1-\alpha_1-\alpha_2\right)\frac{Y_t\Delta_t}{O_t+X_t} && (O_t)\\
0 &= -\lambda_{1t} + \lambda_{2t}E_t\left[\frac{\beta R_t}{C_{t+1}\Pi_{t+1}}\right] - \lambda_{2t-1}\frac{R_{t-1}C_{t-1}}{C_t^2\Pi_t} \\
&\quad +\lambda_{3t}E_t\left[\beta\theta\Pi_{t+1}^{\epsilon-1}D_{t+1} - D_t\right] + \lambda_{4t}E_t\left[\beta\theta\Pi_{t+1}^{\epsilon}N_{t+1} - N_t\right] + \lambda_{10t}L_t^{\psi} && (C_t)\\
0 &= \lambda_{1t} + \lambda_{3t} + \lambda_{4t}\mu mc_t + \lambda_{7t}(1-\alpha_1-\alpha_2)mc_t\Delta_t - \lambda_{8t}\alpha mc_t\Delta_t - \lambda_{9t}\Delta_t && (Y_t)\\
0 &= \lambda_{3t-1}\theta C_{t-1}\Pi_t^{\epsilon-1} - \lambda_{3t}C_t + \lambda_{5t}\left(1-\theta\right)\left(\epsilon-1\right)N_t^{1-\epsilon}D_t^{\epsilon-2} \\
&\quad +\lambda_{6t}(1-\theta)\epsilon N_t^{-\epsilon}D_t^{\epsilon-1} && (D_t)\\
0 &= \lambda_{4t-1}\theta C_{t-1}\Pi_t^{\epsilon} - \lambda_{4t}C_t + \lambda_{5t}\left(1-\theta\right)\left(1-\epsilon\right)N_t^{-\epsilon}D_t^{\epsilon-1} \\
&\quad -\lambda_{6t}(1-\theta)\epsilon N_t^{-\epsilon-1}D_t^{\epsilon} && (N_t)\\
0 &= \lambda_{8t}w_t + \lambda_{9t}\alpha_1 Y_t\Delta_t/L_t + \lambda_{10t}C_t\psi L_t^{\psi-1} && (L_t)\\
0 &= \frac{1}{p_{ot} - Z_t^{-1}} - (O_t + 2X_t)(\lambda_{1t} + \lambda_{7t}) + \lambda_{9t}\left(1-\alpha_1-\alpha_2\right)\frac{Y_t\Delta_t}{O_t+X_t}\Omega_t Z_t \\
&\quad +\lambda_{11t}\phi_o\bar{R}^{1-\phi_R}R_{t-1}^{\phi_R}\left[\frac{\Pi_t}{\bar{\Pi}}\right]^{\phi_\pi}p_{ot}^{\phi_o-1}p_{ot-1}^{-\phi_o} \\
&\quad -\beta E_t\left[\lambda_{11t+1}\bar{R}^{1-\phi_R}R_{t-1}^{\phi_R}\left(\frac{\Pi_{t+1}}{\bar{\Pi}}\right)^{\phi_\pi}p_{ot+1}^{\phi_o}\phi_o p_{ot}^{-\phi_o-1}\right] && (p_{ot})\\
0 &= -\lambda_{2t-1}R_{t-1}\frac{C_{t-1}}{C_t}\Pi_t^{-2} + \lambda_{3t-1}\theta\left(\epsilon-1\right)C_{t-1}\Pi_t^{\epsilon-2}D_t \\
&\quad +\lambda_{4t-1}\theta\epsilon C_{t-1}\Pi_t^{\epsilon-1}N_t + \lambda_{5t}\left(\epsilon-1\right)\theta\Pi_t^{\epsilon-2} \\
&\quad +\lambda_{6t}\theta\epsilon\Pi_t^{\epsilon-1}\Delta_{t-1} + \lambda_{11t}\bar{R}^{1-\phi_R}R_{t-1}^{\phi_R}\phi_\pi\Pi_t^{\phi_\pi-1}\bar{\Pi}^{-\phi_\pi}\left[\frac{p_{ot}}{p_{ot-1}}\right]^{\phi_o} && (\Pi_t)\\
0 &= E_t\left[\lambda_{6t+1}\beta\theta\Pi_{t+1}^{\epsilon}\right] - \lambda_{6t} + \lambda_{7t}(1-\alpha_1-\alpha_2)mc_tY_t - \lambda_{8t}\alpha_1 mc_tY_t - \lambda_{9t}Y_t && (\Delta_t)\\
0 &= \lambda_{4t}\mu Y_t + \lambda_{7t}(1-\alpha_1-\alpha_2)Y_t\Delta_t - \lambda_{8t}\alpha_1Y_t\Delta_t && (mc_t)\\
0 &= \lambda_{2t}\beta E_t\left[\frac{C_t}{C_{t+1}\Pi_{t+1}}\right] - \lambda_{11t} + E_t\left[\lambda_{11t+1}e^{r_t}\beta\phi_R\left(\frac{R_t}{\bar{R}}\right)^{\phi_R-1}\left(\frac{\Pi_{t+1}}{\bar{\Pi}}\right)^{\phi_\pi}\left(\frac{p_{ot+1}}{p_{ot}}\right)^{\phi_o}\right] && (R_t)\\
0 &= \lambda_{8t}L_t - \lambda_{10t} && (w_t)
\end{aligned}
$$

7.2 Output gap derivation

We denote the natural (flexible-price) level of variables with the superscript n, the efficient level of variables with the superscript e, and steady-state variables with an upper bar. We define the output gap $\tilde{y}_t$ as the (log) difference between actual output Y_t and its efficient level Y_t^e. We can express it as a sum of the deviation of actual output from the natural level of output, and the deviation of the natural level of output from the efficient benchmark (and minus a constant which corresponds to the steady state gap),

$$\begin{aligned}\tilde{y}_t &= \log\left(Y_t/\bar{Y}\right) - \log\left(Y_t^e/\bar{Y}^e\right) - \log(\bar{Y}^e/\bar{Y}) \\ &= \log\left(Y_t/\bar{Y}\right) - \log\left(Y_t^n/\bar{Y}\right) + \log\left(Y_t^n/\bar{Y}\right) - \log\left(Y_t^e/\bar{Y}^e\right) - \log(\bar{Y}^e/\bar{Y}) \\ &= \hat{y}_t - \hat{y}_t^n + \tilde{y}_t^n - const\end{aligned}$$

where

$$\begin{aligned}\hat{y}_t &\equiv \log\left(Y_t/\bar{Y}\right) \\ \hat{y}_t^n &\equiv \log\left(Y_t^n/\bar{Y}\right)\end{aligned}$$

and from (86)

$$\tilde{y}_t^n \equiv \log\left(Y_t^n/\bar{Y}\right) - \log\left(Y_t^e/\bar{Y}^e\right) = -\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}(\hat{p}_{ot}^n - \hat{p}_{ot}^e). \tag{88}$$

In section (2.5) we derived equilibrium labor as a function of marginal costs and relative price dispersion:

$$L_t = \left[\frac{\alpha_1 mc_t \Delta_t}{1-(1-\alpha_1-\alpha_2)mc_t\Delta_t}\right]^{\frac{1}{1+\psi}}$$

Under flexible prices labor is constant equal to its steady state value $L_t^n = \bar{L}$.

Combining the production function and the oil demand equation we can write

$$\frac{Y_t}{Y_t^n} = \frac{A_t L_t^{\alpha_1}\bar{K}^{\alpha_2}O_t^{1-\alpha_1-\alpha_2}}{A_t\bar{L}^{\alpha_1}\bar{K}^{\alpha_2}\left(O_t^n\right)^{1-\alpha_1-\alpha_2}} = \left(\frac{L_t}{\bar{L}}\right)^{\alpha_1}\left(\frac{O_{dt}}{O_{dt}^n}\right)^{1-\alpha_1-\alpha_2} \tag{89}$$

$$= \left(\frac{L_t}{\bar{L}}\right)^{\alpha_1}\left(\frac{mc_t\Delta_t}{\mu^{-1}}\right)^{1-\alpha_1-\alpha_2}\left(\frac{Y_t p_{ot}^n}{Y_t^n p_{ot}}\right)^{1-\alpha_1-\alpha_2} \tag{90}$$

$$= \left(\frac{L_t}{\bar{L}}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}}\left(\frac{mc_t\Delta_t}{\mu^{-1}}\right)^{\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}}\left(\frac{p_{ot}^n}{p_{ot}}\right)^{\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} \tag{91}$$

Taking (log) deviations,

$$\hat{y}_t - \hat{y}_t^n = \frac{\alpha_1}{\alpha_1+\alpha_2}\hat{l}_t + \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}(\hat{mc}_t + \hat{\Delta}_t) - \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}(\hat{p}_{ot} - \hat{p}_{ot}^n) \tag{92}$$

Substituting (88) and (92) into the expression for the (welfare-relevant) output gap, we obtain

$$\tilde{y}_t = \frac{\alpha_1}{\alpha_1+\alpha_2}\hat{l}_t + \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}\left(\hat{mc}_t + \hat{\Delta}_t\right) - \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}\left(\hat{p}_{ot} - \hat{p}_{ot}^e\right) - const.$$

Up to a first-order approximation then we have,

$$\tilde{y}_t = \kappa_{mc}\hat{mc}_t - \kappa_\nu\hat{\nu}_t^n, \tag{93}$$

where

$$\begin{aligned}\kappa_{mc} &= \left[\frac{\mu(1-\frac{\psi}{1+\psi}\alpha_1+\alpha_2) - (1+\alpha_1+\alpha_2)(1-\alpha_1-\alpha_2)}{(\alpha_1+\alpha_2)(\mu-1+\alpha_1+\alpha_2)}\right], \\ \kappa_\nu &= \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}.\end{aligned}$$

7.3 Proof of proposition 2

The model can be represented by the following equations:

Resource constraint,

$$C_t = Y_t - p_{ot}O_{dt}.$$

Production function (let $\tilde{A}_t \equiv A_t K^{\alpha_2}$),

$$Y_t = \tilde{A}_t L_t^{\alpha_1} O_{dt}^{1-\alpha_1-\alpha_2}/\Delta_t.$$

Using $w_t L_t = \alpha_1 mc_t Y_t \Delta_t$ and $w_t L_t = C_t L_t^{1+\psi}$ we can write the equilibrium labor equation ,

$$C_t L_t^{1+\psi} = \alpha_1 mc_t Y_t \Delta_t.$$

Using the oil demand curve $p_{ot}O_{dt} = (1-\alpha_1-\alpha_2)mc_t Y_t \Delta_t$ and the above equation we can write

$$p_{ot}O_{dt} = \frac{1-\alpha_1-\alpha_2}{\alpha_1} C_t L_t^{1+\psi}$$

Targeting oil revenues is equivalent to targeting a weighted average of consumption and labor.

The previous four equations provide a full description of the behavior of the private sector except for the behavior of marginal costs. With sticky prices marginal costs are not constant in general and are related to the price setting decision of firms. These are summarized in the last four constraints of the policy problem below. A benevolent monetary policy maker would maximize the following Lagrangian:

$$\begin{aligned}
&\max\ E_0 \sum_{t=0}^{\infty} \beta^t \Bigg\{ \log C_t - \frac{L_t^{1+\psi}}{1+\psi} \\
&+\lambda_{1t}\left[Y_t - p_{ot}O_{dt} - C_t\right] \\
&+\lambda_{2t}\left[\frac{1-\alpha_1-\alpha_2}{\alpha_1} C_t L_t^{1+\psi} - p_{ot}O_{dt}\right] \\
&+\lambda_{3t}\left[\tilde{A}_t L_t^{\alpha_1} O_{dt}^{1-\alpha_1-\alpha_2}/\Delta_t - Y_t\right] \\
&+\lambda_{4t}\left[\alpha_1 mc_t Y_t \Delta_t - C_t L_t^{1+\psi}\right] \\
&+\lambda_{5t}\left[Y_t + \beta\theta C_t E_t\left[\Pi_{t+1}^{\epsilon-1} D_{t+1}\right] - C_t D_t\right] \\
&+\lambda_{6t}\left[\mu mc_t Y_t + \beta\theta C_t E_t\left(\Pi_{t+1}^{\epsilon} N_{t+1}\right) - C_t N_t\right] \\
&+\lambda_{7t}\left[\theta\Pi_t^{\epsilon-1} + (1-\theta)\left(\frac{N_t}{D_t}\right)^{1-\epsilon} - 1\right] \\
&+\lambda_{8t}\left[\theta\Pi_t^{\epsilon}\Delta_{t-1} + (1-\theta)\left(\frac{1-\theta\Pi_t^{\epsilon-1}}{1-\theta}\right)^{\frac{\epsilon}{\epsilon-1}} - \Delta_t\right]\Bigg\}
\end{aligned}$$

System of first-order conditions for the first five variables:

$$1/C_t - \lambda_{1t} + \frac{p_{ot}O_{dt}}{C_t}\lambda_{2t} - L_t^{1+\psi}\lambda_{4t} - \lambda_{5t}Y_t/C_t - \lambda_{6t}\mu mc_t Y_t/C_t = 0 \qquad (C_t)$$

$$-L_t^{\psi} + (1+\psi)\lambda_{2t}\frac{p_{ot}O_{dt}}{L_t} + \alpha_1\lambda_{3t}Y_t/L_t - (1+\psi)C_t L_t^{\psi}\lambda_{4t} = 0 \qquad (L_t)$$

$$p_{ot}O_{dt}(\lambda_{1t} + \lambda_{2t}) - (1-\alpha_1-\alpha_2)Y_t\lambda_{3t} = 0 \qquad (O_{dt})$$

$$\lambda_{1t} - \lambda_{3t} + \alpha_1 mc_t\Delta_t\lambda_{4t} + \lambda_{5t} + \mu mc_t\lambda_{6t} = 0 \qquad (Y_{dt})$$

$$\alpha_1\Delta_t\lambda_{4t} + \mu\lambda_{6t} = 0 \qquad (mc_t)$$

From the previous block of equations we can establish some relevant relations as follows:

$$\lambda_{3t} = \frac{1}{(\alpha_1+\alpha_2)Y_t}$$

$$\lambda_{5t} = \lambda_{3t} - \lambda_{1t}$$

$$\lambda_{6t} = -\lambda_{4t}\frac{\alpha_1\Delta_t}{\mu}$$

$$p_{ot}O_{dt}\left(\lambda_{2t} - \frac{\alpha_1}{1-\alpha_1-\alpha_2}\lambda_{4t}\right) = \frac{L_t^{1+\psi}}{(1+\psi)} - \frac{\alpha_1}{(1+\psi)(\alpha_1+\alpha_2)}$$

The second block of first-order conditions is:

$$\alpha_1 mc_t Y_t\lambda_{4t} + \lambda_{8t+1}\beta\theta\Pi_{t+1}^{\epsilon} - \lambda_{8t} = \frac{Y_t}{\Delta_t}\lambda_{3t} = \frac{1}{(\alpha_1+\alpha_2)\Delta_t} \qquad (\Delta_t)$$

$$\lambda_{5t-1}\theta C_{t-1}\Pi_t^{\epsilon-1} - C_t\lambda_{5t} = \lambda_{7t}(1-\theta)(1-\epsilon)N_t^{1-\epsilon}D_t^{\epsilon-2} \qquad (D_t)$$

$$\lambda_{6t-1}\theta C_{t-1}\Pi_t^{\epsilon-1} - C_t\lambda_{6t} = -\lambda_{7t}(1-\theta)(1-\epsilon)N_t^{-\epsilon}D_t^{\epsilon-1} \qquad (N_t)$$

$$\lambda_{5t-1}(\epsilon-1)\Pi_t^{\epsilon-2}D_tC_{t-1} + \lambda_{6t-1}\epsilon\Pi_t^{\epsilon-1}N_tC_{t-1} + \lambda_{7t}(\epsilon-1)\Pi_t^{\epsilon-2} +$$
$$+\lambda_{8t}\epsilon\left[\Pi_t^{\epsilon-1}\Delta_{t-1} - \left(\frac{1-\theta\Pi_t^{\epsilon-1}}{1-\theta}\right)^{\frac{1}{\epsilon-1}}\Pi_t^{\epsilon-2}\right] = 0 \qquad (\Pi_t)$$

In what follows we guess and verify that zero inflation is a solution.

From the law of motion of inflation, assuming $\Pi_t = 0$ implies $N_t = D_t$. In addition, starting from $\Delta_{-1} = 0$ we have $\Delta_t = 1$. Hence for marginal costs we have:

$$\sum_{j=0}^{\infty}(\beta\theta)^j E_t\frac{Y_{t+j}}{C_{t+j}}(1-\mu mc_{t+j}) = 0.$$

A possible solution is $mc_t = \mu^{-1}$. This implies that $L_t = L$ and Y/C are constant. Hence D_t is constant as well:

$$D_t = \sum_{j=0}^{\infty}(\beta\theta)^j E_t\frac{Y_{t+j}}{C_{t+j}} = \frac{\mu}{\mu-1+\alpha_1+\alpha_2}\frac{1}{1-\beta\theta}$$

We can rewrite the last block of equations using our guess:

$$\begin{aligned}
\alpha_1/\mu Y_t \lambda_{4t} + \lambda_{8t+1}\beta\theta - \lambda_{8t} &= \frac{1}{\alpha_1+\alpha_2} \\
\lambda_{5t-1}\theta C_{t-1} - C_t\lambda_{5t} &= \lambda_{7t}(1-\theta)(1-\epsilon)/D \\
\lambda_{6t-1}\theta C_{t-1} - C_t\lambda_{6t} &= -\lambda_{7t}(1-\theta)(1-\epsilon)/D \\
\lambda_{5t-1}(\epsilon-1)C_{t-1} + \lambda_{6t-1}\epsilon C_{t-1} &= \lambda_{7t}(1-\epsilon)/D
\end{aligned}$$

A recursive solution consistent with the timeless perspective requires to set $\lambda_{5,-1} + \lambda_{6,-1} = 0$:

$$\begin{aligned}
\lambda_{5t} &= -\lambda_{6t} \\
C_t\lambda_{6t} &= C_{t-1}\lambda_{6t-1} \\
\lambda_{7t} &= \frac{D}{1-\epsilon}C_t\lambda_{6t} \\
\lambda_{4t} &= -\frac{\mu}{\alpha_1}\lambda_{6t} \\
(1-\beta\theta)^{-1}\lambda_{8t} &= -1/(\alpha_1+\alpha_2) - \frac{Y}{C}C_t\lambda_{6t} \\
\lambda_{1t} &= \lambda_{3t} - \lambda_{5t}.
\end{aligned}$$

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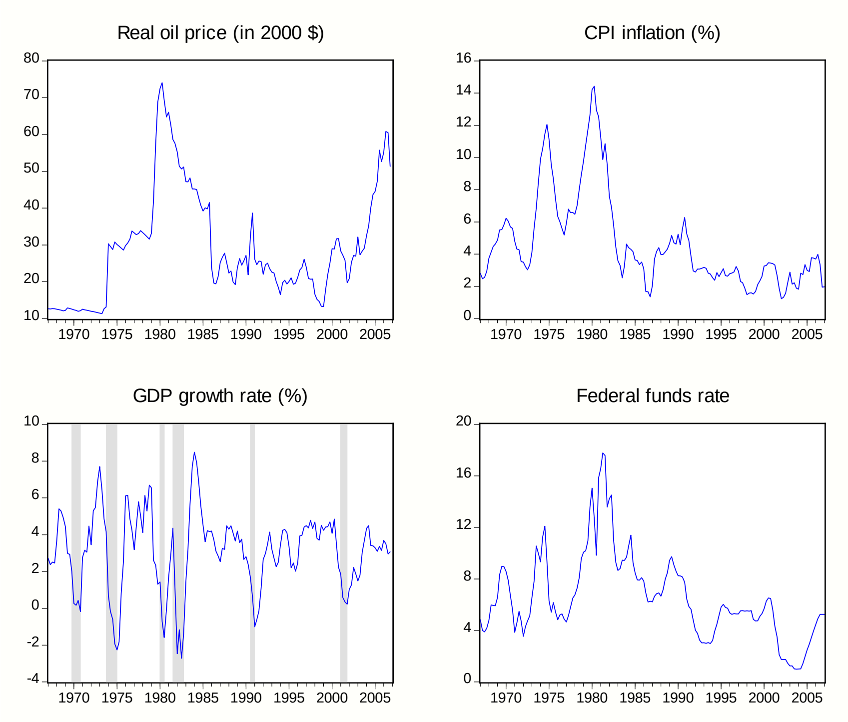

Figure 1: Price of oil, inflation, growth and Fed rate

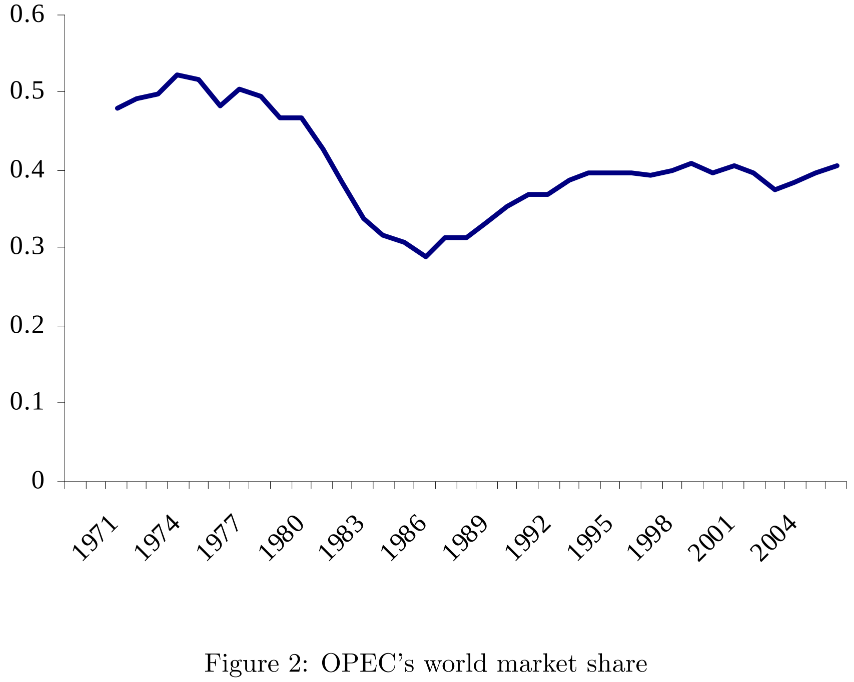

Figure 2: OPEC's world market share

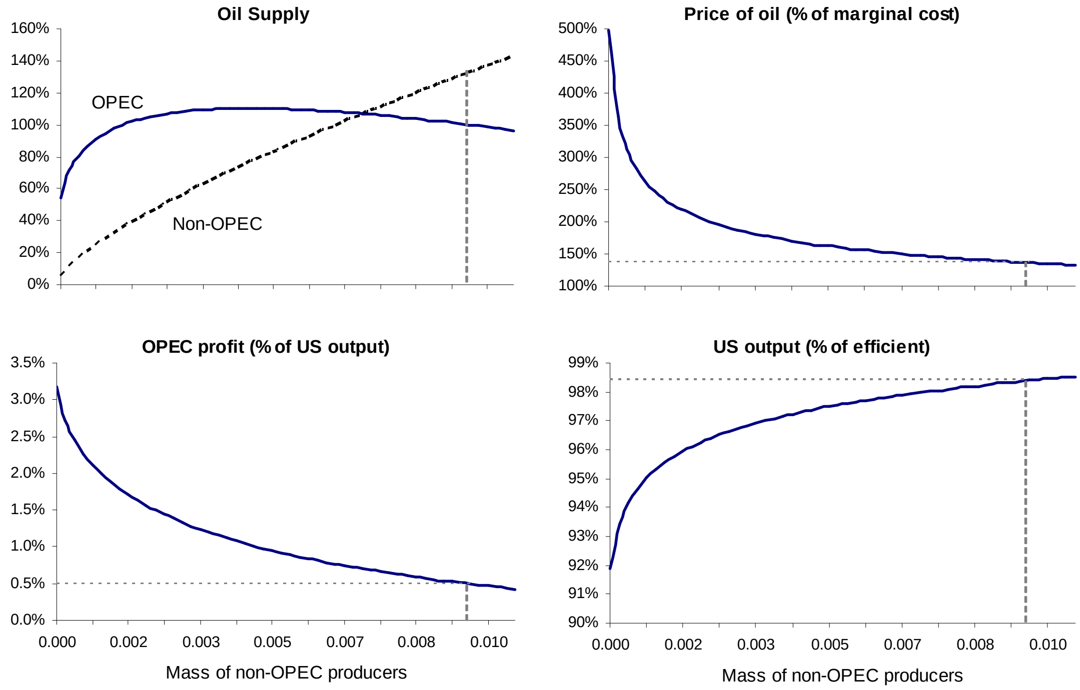

Figure 3: Comparative statics: mass of non-OPEC producers ($\bar{\Omega}$)

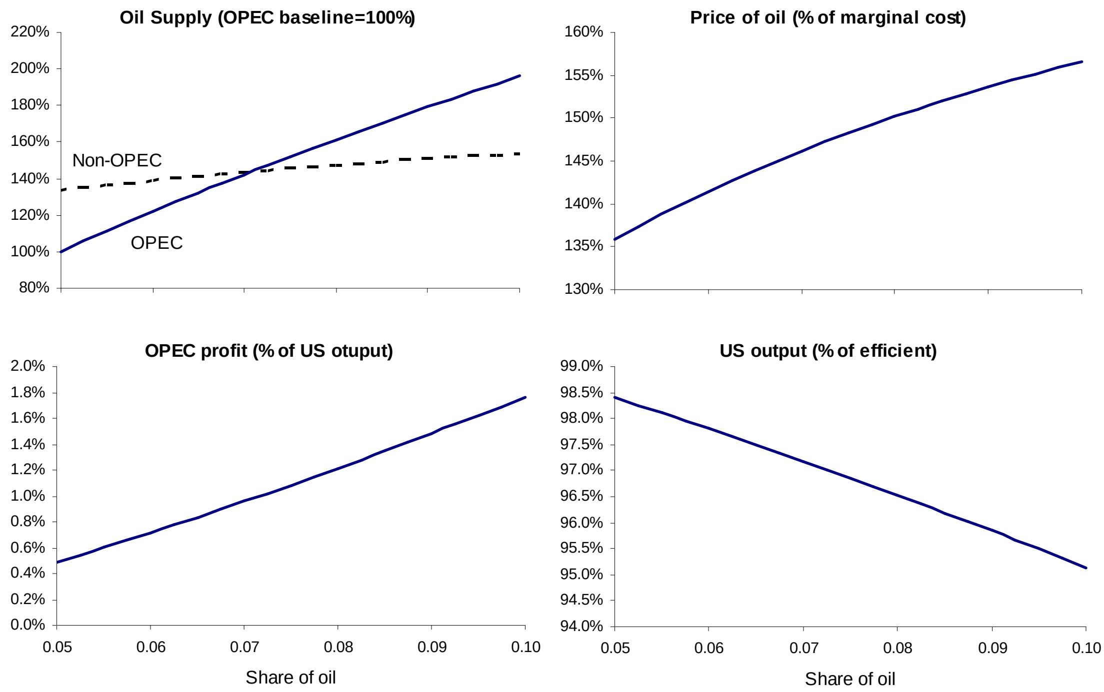

Figure 4: Comparative statics: elasticity of oil in production (keeping the mass of non-OPEC constant)

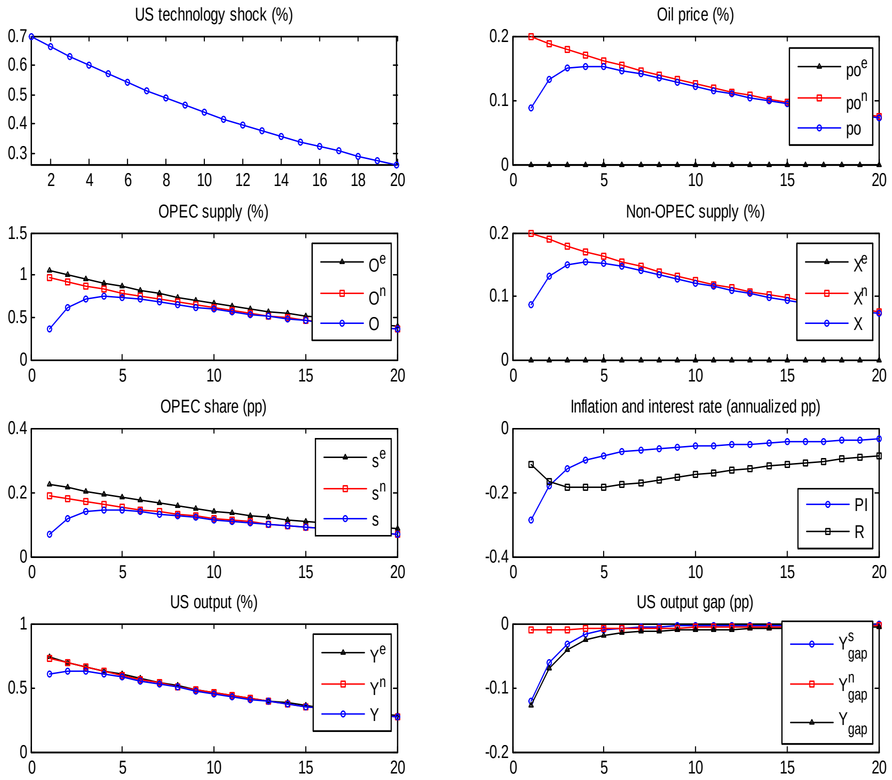

Figure 5: Responses to a positive US TFP shock

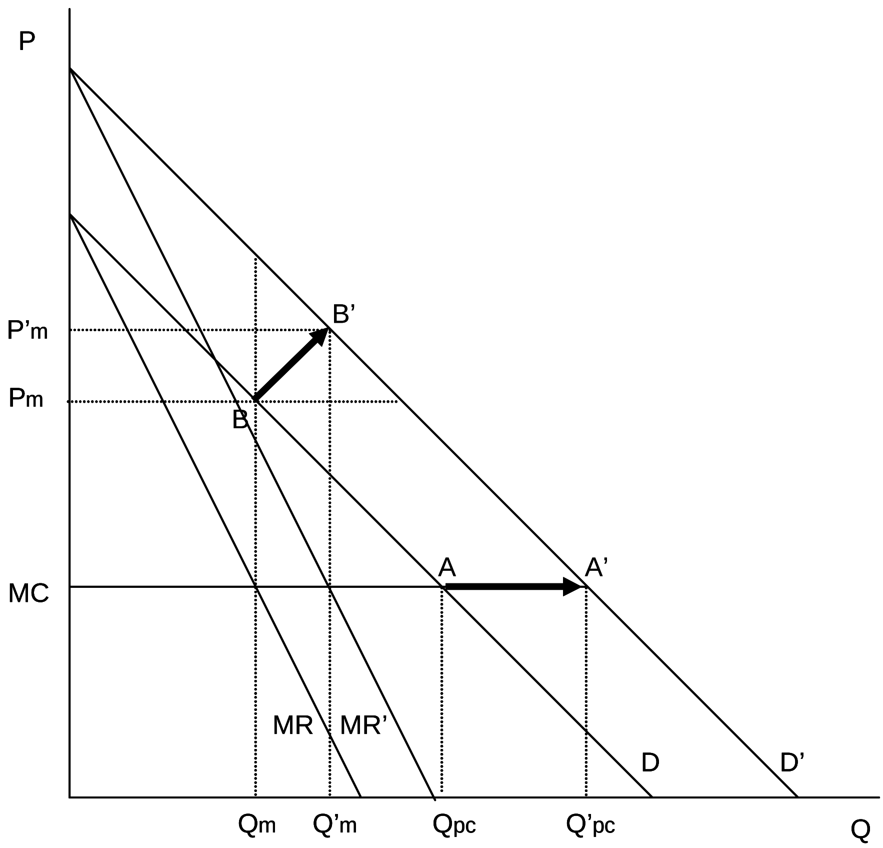

Figure 6: Competitive and monopoly response to a positive demand shock.

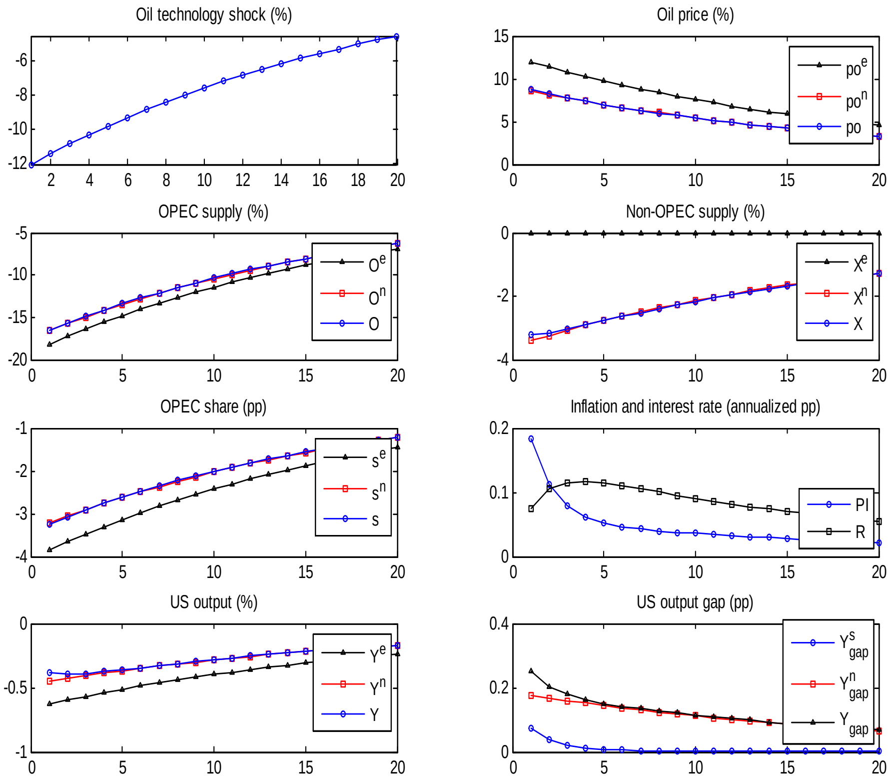

Figure 7: Responses to a negative oil technology shock

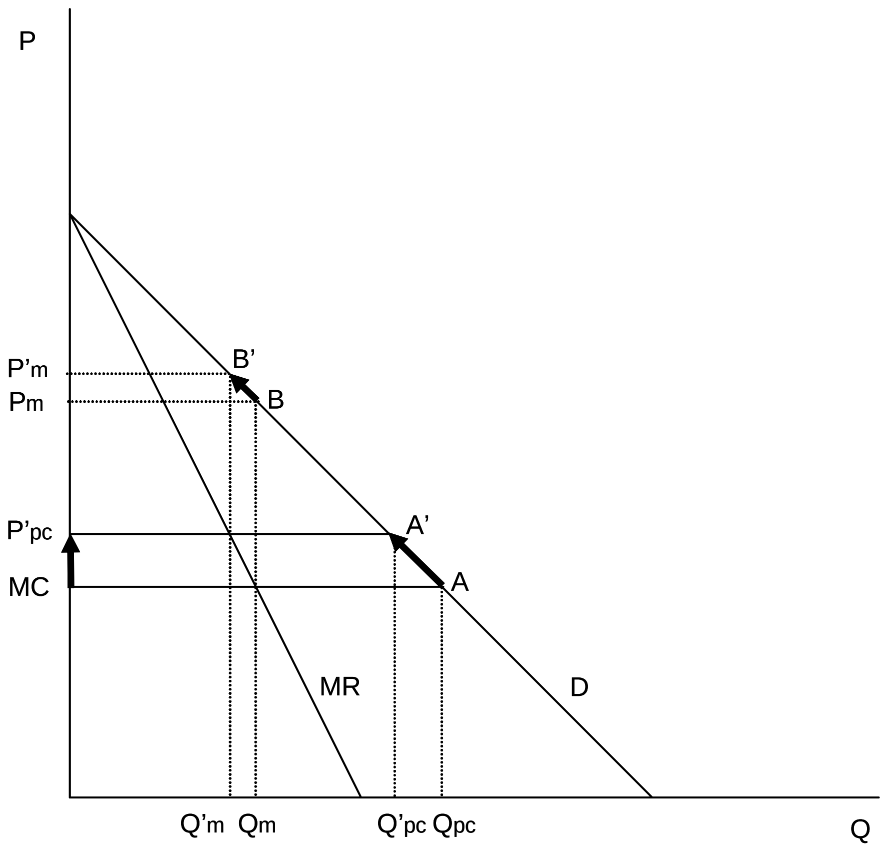

Figure 8: Competitive and monopoly response to an oil technology shock.

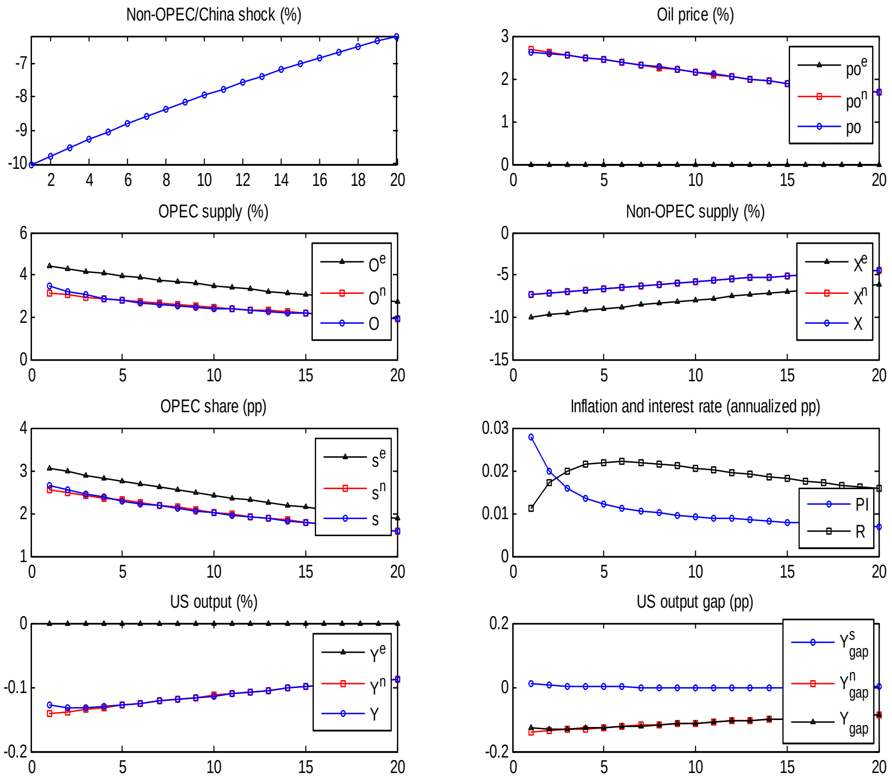

Figure 9: Responses to a negative fringe capacity shock

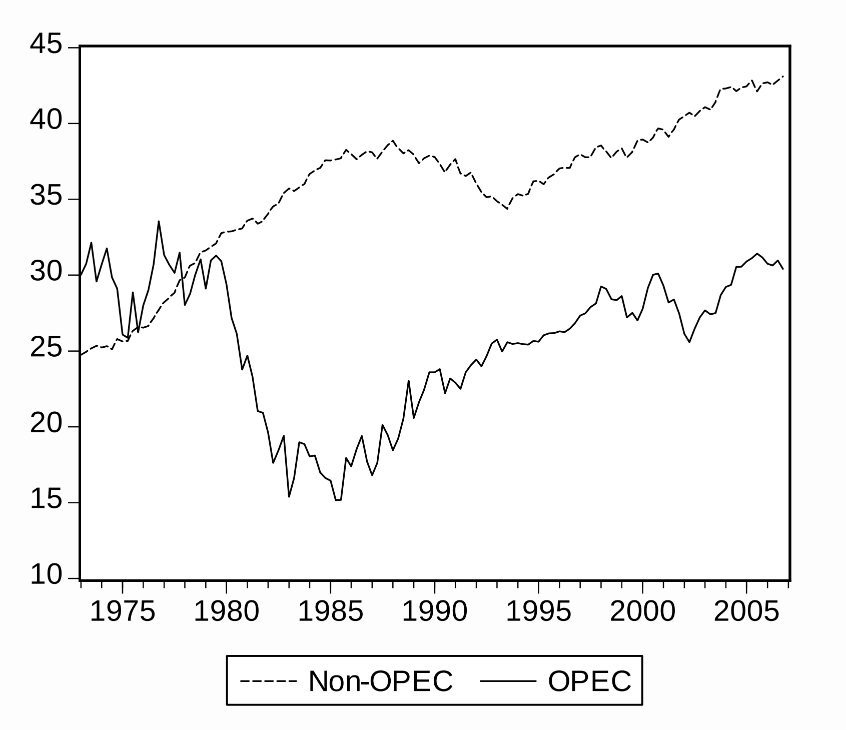

Figure 10: OPEC and non-OPEC oil supply (million barrels per day)

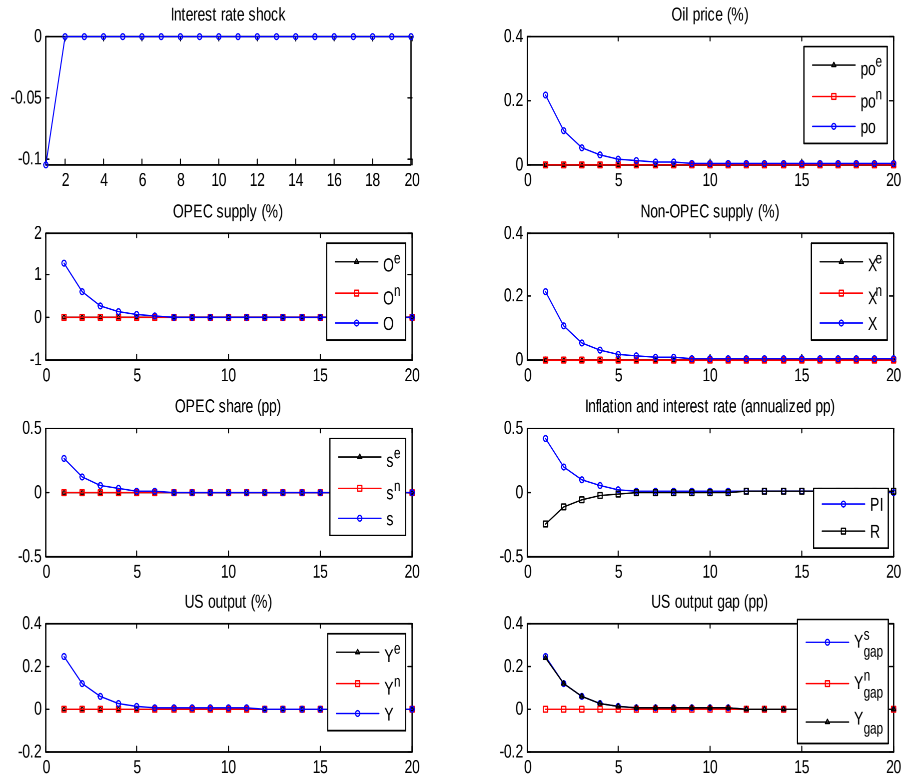

Figure 11: Responses to a negative interest rate shock

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