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Inflation-Output Gap Trade-off with a Dominant Oil Supplier

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An exogenous oil price shock raises infation and contracts output, similar to a negative productivity shock. In the standard New Keynesian model, however, this does not generate any trade-off between infation and output gap volatility: under a strict infation targeting policy, the output decline is exactly equal to the efficient output contraction in response to the shock. Modeling the oil sector from optimizing rst principles rather than assuming an exogenous oil price, we show that the presence of a dominant oil supplier (OPEC) leads to inefficient fluctuations in the oil price markup. The latter refects a dynamic distortion of the production process, and as a result stabilizing infation does not automatically stabilize the distance of output from rst-best. Our model is a step 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.

Key words: Monetary Policy, Oil industry, OPEC, Competitive Fringe, Business Cycle.

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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 1970s 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 that 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 stabilize 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 a negative productivity shock—which in that framework is equivalent to an exogenous oil price increase—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 price 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 the welfare of its owner, 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 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 may find it desirable to either raise or lower the interest rate in order to improve the real allocation.

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 advocat-

[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.

ing a uniform Taylor-type reaction to changes in the oil *price* (and indeed we show that, in general, the latter policy may not improve much on a 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 importer and an oil exporter—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 monopoly power exerted 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 (see Gali 2001 and Rotemberg and Woodford 1997) with oil included as an additional input in production, monopolistic competition, and infrequent price adjustments. 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, and labor L, and we assume that it takes the form

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

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 domestically traded bonds, B_{t-1}, to outlays on consumption, $P_t C_t$, and bonds, $B_t R_t^{-1}$. The aggregate stock of capital that 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

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

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 economywide 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,

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

subject to a downward-sloping demand schedule,

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

where $Q_{t+k}(i)$ is demand for the output of firm i, $C\left(Q_{t+k}(i)\right)$ 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 (OPEC) is endowed with an oil field of unbounded capacity. Oil, O_t, is produced according to

$$O_t = Z_t \tilde{I}_t, \tag{11}$$

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

$$z_t = \rho_z z_{t-1} + \varepsilon_t^z, \tag{12}$$

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

The country is populated by a representative household that enjoys an expected present discounted flow of consumption-utility streams,

$$E_o \sum_{t=0}^{\infty} \beta^t U(\tilde{C}_t), \tag{13}$$

where the period utility function is logarithmic in consumption,

$$U\left(\tilde{C}_t\right) = \log(\tilde{C}_t). \tag{14}$$

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.

The household's consumption is determined by the surplus from oil production,

$$P_t \tilde{C}_t = p_{ot} O_t - \tilde{I}_t, \tag{15}$$

where p_{ot} is the price of oil.

OPEC acts as a planner allocating expenditure among the different intermediate and final goods so as to minimize the cost of buying the aggregate bundles $\tilde{I}_t$ and $\tilde{C}_t$; at time 0, it announces and commits to a state-contingent path of oil output, $\{O_{t+j}\}_{j=0}^{\infty}$, so as to maximize the expected present discounted utility of the representative household-owner of OPEC, subject to the behavior of competitive oil exporters, and to the private sector and monetary authority in the U.S.

2.2.2 Competitive Fringe of Small Oil Exporters

The rest of the world is populated by a representative household owning 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

$$X_t(i) = \xi(i) Z_t \hat{I}_t(i), \tag{16}$$

subject to the capacity constraint,

$$X_t(i) \in [0, \bar{X}], \tag{17}$$

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 of the environment, while $1/\xi(i)$ is a constant, non-negative, firm-specific component distributed according to some probability distribution function $F(.)$. Profits from the oil firms are rebated lump sum to the representative household. The input $\hat{I}_t(i)$ is purchased from the US as is the aggregate consumption bundle of the representative household populating the rest of the world, $\hat{C}_t$; both $\hat{I}_t(i)$ and $\hat{C}_t$ 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,

$$\hat{\omega}_t = \rho_\omega \hat{\omega}_{t-1} + \varepsilon_t^\omega \tag{18}$$

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; 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 that induces a negative correlation between the supply of OPEC and the output of the competitive fringe, a feature of the data that is prominent in the 1980s and early 1990s (see figure 10).

The produced oil can 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,

$$\max \left\{ p_{ot} X_t(i) - \frac{X_t(i)}{Z_t \xi(i)} \right\} \tag{19}$$

$$\text{s.t.}$$

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

Any single oil firm is profitable and active if and only if the current market price of oil p_{ot} is greater than its marginal cost. Thus, competitive oil firm i

produces $\bar{X}$ if $[\xi(i)Z_t]^{-1} \leq p_{ot}$ and zero otherwise. Hence, the amount of oil produced by the competitive fringe as a whole is given by

$$X_t \equiv \int_0^{\Omega_t} X_t(i)di = \Omega_t F(p_{ot} Z_t) \tag{20}$$

In what follows, we assume that the idiosyncratic component of marginal costs $1/\xi(i)$ is distributed uniformly in the interval $[a, b] \subset \mathbb{R}_+$. In that case

$$X_t = \begin{cases} \Omega_t \bar{X}, & p_{ot} Z_t > b \\ \Omega_t \bar{X} \frac{p_{ot} Z_t - a}{b - a}, & a < p_{ot} Z_t \leq b \\ 0, & p_{ot} Z_t \leq a \end{cases} \tag{21}$$

We further assume without loss of generality that $a = 0$ and normalize $b = \bar{X} > 1$ which we choose sufficiently large such that at least some competitive fringe producers (or potential entrants) are always priced out of the market by the dominant oil firm.[7] With these assumptions the output of the competitive fringe is a product of the price of oil (p_{ot}), aggregate 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):

$$X_t = \Omega_t p_{ot} Z_t. \tag{22}$$

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 about 50% in the 1970s, then dropped down to 30% in the 1980s, before recovering to about 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 is what ultimately breaks the "divine coincidence" between stabilizing inflation and stabilizing the welfare-relevant output gap, creating a tension between the two stabilization objectives.

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

2.3 Equilibrium Conditions

A full derivation of the optimality, aggregation, and market clearing conditions is given in the appendix, here we describe the most important relations that link the US economy and the oil-exporting countries.

Cost minimization of oil-importing firms implies the following demand for labor and oil as factors of production:

$$p_{ot}O_{dt} = (1-\alpha_1-\alpha_2)mc_tQ_t\Delta_t, \quad (23)$$

$$w_tL_t = \alpha_1 mc_tQ_t\Delta_t, \quad (24)$$

where w_t is the real wage, O_{dt} is the US oil demand, and mc_t are real marginal costs, which are common across all firms. The variable $\Delta_t \geq 1$ is a measure of relative price dispersion[8] which acts as a tax on final goods production, $Q_t = A_tL_t^{\alpha_1}\bar{K}^{\alpha_2}O_{dt}^{1-\alpha_1-\alpha_2}/\Delta_t$.

The lack of borrowing across regions implies that total US consumption must be equal to US value added (or GDP), Y_t, which is simply total final goods production net of the oil imports,

$$Y_t = C_t = Q_t - p_{ot}O_{dt}. \quad (25)$$

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

$$O_{dt} = O_t + X_t. \quad (26)$$

Finally, we can verify that the following aggregate resource constraint holds,

$$Q_t = C_t + \tilde{C}_t + \tilde{I}_t + \hat{C}_t + \hat{I}_t, \quad (27)$$

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

2.4 Flexible Price Benchmarks

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

First of all notice that, regardless of the oil sector market structure, under flexible prices (attained by setting $\theta = 0$) there is no final goods price dispersion, $\Delta_t = 1$, and marginal costs are constant and equal to the inverse of the optimal

[8] Precisely, $\Delta_t \equiv \int_0^1 \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} di$.

markup of final goods firms (related to the elasticity of substitution among final goods) $mc_t = \mu^{-1} = \frac{\epsilon-1}{\epsilon}$. This, coupled with our assumptions on preferences and technology, implies that hours worked are constant, independent of shocks, $L_t = \bar{L} = \left[\frac{\alpha_1}{\mu-(1-\alpha_1-\alpha_2)}\right]^{\frac{1}{1+\psi}}$.

2.4.1 Efficiency: perfect competition in oil and flexible prices

Under the efficient allocation (denoted by the superscript "e"), we can think of the OPEC cartel as dissolved and the large oil field with unbounded capacity as operated by a continuum of competitive oil firms.[9] The real price of oil is then equal to the marginal cost of the large oil field's marginal producer[10]

$$p^e_{ot} = mc_{ot} = Z_t^{-1}, \tag{28}$$

which is exogenously given.

On the other hand, oil demand (23) becomes

$$p^e_{ot}O^e_{dt} = (1-\alpha_1-\alpha_2)\mu^{-1}Q^e_t \tag{29}$$

while the oil produced by the large oil field is

$$O_t = O_{dt} - \Omega_t.$$

We can establish the following

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 (28) and (29) combined with (66) imply

$$Q^e_t = \left[A_t Z_t^{1-\alpha_1-\alpha_2}\right]^{\frac{1}{\alpha_1+\alpha_2}} \bar{L}^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \bar{K}^{\frac{\alpha_2}{\alpha_1+\alpha_2}} \left[(1-\alpha_1-\alpha_2)\mu^{-1}\right]^{\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} \tag{30}$$

Labor and real marginal costs are constant, and all other real endogenous variables of the oil importer (w^e_t, r^e_t, C^e_t, and O^e_{dt}) can be expressed in terms of Q^e_t.[11] ■

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): those shocks are observationally equivalent.

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

[10] 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 the oil field with unbounded capacity out of the market. This happens whenever $\Omega_t^{\alpha_1+\alpha_2} > A^o_t Z_t$, which implies $O_t = 0$ and $p^e_{ot} = \left[A^o_t(\Omega_t Z_t)^{-\alpha_1-\alpha_2}\right]^{1/(1+\alpha_1+\alpha_2)} < 1/Z_t$.

[11] For example, the efficient level of consumption (or value added) is given by $C^e_t = (1-(1-\alpha_1-\alpha_2)\mu^{-1})Q^e_t$.

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

2.4.2 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 initial price dispersion, 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.

2.4.3 Natural allocation: market power in oil and flexible prices

We now turn to the natural allocation (denoted by the superscript "n"). Exploiting the fact that equilibrium labor is a constant, and combining the production function with the oil share equation (23), we can derive a relationship between the oil price and the demand for oil,

$$p^n_{ot} = A^o_t (O^n_{dt})^{-\alpha_1 - \alpha_2}, \tag{31}$$

where $A^o_t \equiv (1 - \alpha_1 - \alpha_2)\mu^{-1} A_t \bar{L}^{\alpha_1} \bar{K}^{\alpha_2}$ is an oil demand shifter driven by US TFP shocks.

Consecutive substitution of (22) and (26) into the above equation (31) yields an oil demand curve that 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 (see eq. (75) in the Appendix) since now the only relevant constraint for the maximization of profits is a single demand curve (33). Hence, OPEC solves

$$\max_{O^n_t} \; E_0 \sum_{t=0}^{\infty} \beta^t \log[p^n_{ot} O^n_t - O^n_t / Z_t] \tag{32}$$

$$\text{s.t.} \qquad p_{ot}^n \left(O_t^n + \Omega_t p_{ot}^n Z_t\right)^{\alpha_1+\alpha_2} = A_t^o \tag{33}$$

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

$$p_{ot}^n = \nu_t^n mc_{ot}, \tag{34}$$

where the marginal cost is given by $mc_{ot} = Z_t^{-1} = p_{ot}^e$, while the optimal markup is inversely related to the (absolute) price elasticity of demand for OPEC's oil:[12]

$$\nu_t^n = \frac{\left|\varepsilon_t^{O^n,\, p_o^n}\right|}{\left|\varepsilon_t^{O^n,\, p_o^n}\right| - 1}. \tag{35}$$

The latter can be derived from constraint (33) as

$$\left|\varepsilon_t^{O^n,\, p_o^n}\right| \equiv \left|\frac{\partial O_t^n}{\partial p_{ot}^n} \frac{p_{ot}^n}{O_t^n}\right| = \frac{1}{\eta s_t^n} - 1, \tag{36}$$

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 (36) 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 that increases OPEC's market share makes the demand for OPEC's oil less price elastic, raising the optimal markup charged by OPEC.

Substituting (36) into (35) we can obtain a direct relationship between the optimal oil price markup and the market share of the dominant oil exporter,

$$\nu_t^n = \frac{1 - \eta s_t^n}{1 - 2\eta s_t^n}, \tag{37}$$

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,

$$corr(\nu_t^n,\ s_t^n) \approx 1. \tag{38}$$

[12] The inverse of the oil markup can also be written as $1/\nu_t^n = 1 - \frac{(\alpha_1+\alpha_2)O_t}{O_t + (1+\alpha_1+\alpha_2)X_t}$.

2.4.4 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:

$$O_t^m = [(1-\alpha_1-\alpha_2)A_t^o Z_t]^{\frac{1}{\alpha_1+\alpha_2}} , \tag{39}$$

$$p_{ot}^m = \frac{1}{Z_t\,[1-\alpha_1-\alpha_2]} = \nu^m p_{ot}^e \tag{40}$$

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 (36) reduces to

$$\left|\varepsilon_t^{O^m,\, p_o^m}\right| = \left|\frac{\partial O_t^m}{\partial p_{ot}^m}\frac{p_{ot}^m}{O_t^m}\right| = \frac{1}{\alpha_1+\alpha_2} = \frac{1}{1-(1-\alpha_1-\alpha_2)}. \tag{41}$$

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 that is an order of magnitude lower than the full monopoly markup,

$$s_t^n = 0.5 \Longrightarrow \nu^n = 1 + \frac{\alpha_1+\alpha_2}{2} = 1.475 << \nu^m = 20. \tag{42}$$

2.4.5 The natural GDP gap

We define the "natural GDP gap" as the distance between the natural level of value added, Y_t^n, and its efficient counterpart, Y_t^e, and denote this distance by $\hat{Y}_t^n$. 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 (34) and (28) is equal to the oil price markup in the natural allocation,

$$\hat{Y}_t^n \equiv Y_t^n/Y_t^e = Q_t^n/Q_t^e = (p_{ot}^n/p_{ot}^e)^{-\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} = (\nu_t^n)^{-\frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}} . \tag{43}$$

Since we have seen in (35) 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 (and hence the average markup of final goods producers), it would make sense to counter, at least to some extent, fluctuations in the oil price markup, in addition to targeting inflation.

2.5 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 final goods producers' markup), and indirectly the demand for and price of oil.

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, that satisfy constraints (76) - (87) and solve the dominant oil supplier's problem in (75).

We derive an expression for the *welfare-relevant* GDP gap, $\tilde{y}_t$ (to which we refer sometimes simply as "the output gap"), defined as the (log) distance between actual value added and its efficient level given by (30),

$$\tilde{y}_t \equiv y_t - y_t^e.$$

As shown in Appendix 2, this gap is related to real marginal costs mc_t—a standard result in the New Keynesian literature—but in our model also to the oil price markup. Thus, up to a first-order approximation, fluctuations in the output gap are related to shifts in these two variables,

$$\tilde{y}_t = \kappa_{mc}\hat{mc}_t - \kappa_\nu \hat{\nu}_t, \qquad (44)$$

where $\kappa_{mc} > 0$ and $\kappa_\nu > 0$ are related to the structural parameters of the model and are defined in the Appendix; $\hat{mc}_t$ are real marginal costs in the final goods sector and $\hat{\nu}_t = \hat{p}_{ot} - \hat{p}_{ot}^e$ is the oil price markup, both in log-deviations from the efficient equilibrium.[13]

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

From equation (44) 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 value added and its natural level. Yet this would not stabilize fully the welfare-relevant output gap,

$$\tilde{y}_t = (y_t - y_t^n) + (y_t^n - y_t^e),$$

[13] Notice that defining the output gap in terms of gross output instead of value added yields an identical expression with a minor reparametrization of κ_{mc} (provided the share of oil in GDP is not large).

since in response to real shocks OPEC's profit-maximizing behavior induces inefficient fluctuations in the oil price markup $\hat{\nu}_t$, reflected in a time-varying wedge between the natural and the efficient level of output. 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.

2.6 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 about 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.[14] 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 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.[15] Finally, the interest

[14] More on this in the following section.

[15] 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.

rate shock is assumed to be *i.i.d.* with standard deviation corresponding to a 25 basis point disturbance of the interest rate rule.

In the following section we study the steady-state properties of the model and perform comparative statics exercises varying some of the above parameters.

Structural parameters		
Quarterly discount factor	β	0.9926
Elasticity of output wrt labor	α_1	0.63
Elasticity of output wrt capital	α_2	0.32
Elasticity of output wrt. oil		0.05
Price adjustment probability	θ	0.75
Price elasticity of substitution	ϵ	7.66
Mean of non-OPEC capacity	$\bar{\Omega}$	0.0093
Inv. Frisch labor supply elast.	ψ	1
Monetary policy		
Long run inflation target	$\bar{\Pi}$	1
Interest rate smoothing coeff.	ϕ_R	0.8
Inflation reaction coefficient	ϕ_π	0.4
Oil price reaction coefficient	ϕ_{po}	0
Shock processes		
Std of US TFP shock	σ_a	0.007
Persistence of US TFP shock	ρ_a	0.95
Std of oil tech. shock	σ_z	0.12
Persistence of oil tech. shock	ρ_z	0.95
Std of non-OPEC capacity	σ_ω	0.10
Persist. of non-OPEC capacity	ρ_ω	0.975
Std dev of int. rate innovation	σ_r	0.001

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.

The zero inflation steady-state is characterized by an inefficiently low oil supply by OPEC[16], 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 about 36% over marginal cost, and make a positive profit of about 0.5% of U.S. output (or about $65 billion per annum based on nominal U.S. GDP in 2006). At the same time, imperfect

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

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 (37) 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 non-linear 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 to 0.1 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)).[17] 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 GDP gap measures: the actual (or welfare-relevant GDP gap, denoted by Y_{gap}), the natural GDP gap (denoted by Y^n_{gap}), and the "sticky price GDP gap" (denoted by Y^s_{gap}), defined as the distance between the actual and the natural level of GDP.

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

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

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.[18] 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.[19]

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 (37) and (38). 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 GDP 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 GDP gap.

Finally, consider the actual allocation with nominal rigidity and given the benchmark policy rule (10). Inflation falls by about 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, where nearly all of the 13 basis point fall (that is, widening) of the GDP gap induced by the shock is attributable to the fall of the "sticky price GDP gap" (Y^s_{gap}). Hence, there is almost no tradeoff between inflation and GDP gap stabilization. Compared to the benchmark Taylor-type rule, a positive technology shock calls for a somewhat more aggressive interest rate *reduction* even if the shock is associated with a slightly rising oil price.

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

[19] 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'.

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 completely 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 (about 9%) is less than the efficient increase (of 12%).[20] 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 about 3%, while OPEC's market share declines by about 3 percentage points, shadowing the movement of the oil price markup.

Actual US GDP falls by about 0.4%, which is less than the efficient decline of 0.65%.[21] As a result, the rise in inflation by 20 basis points is accompanied by an increase (that is, narrowing) of the GDP gap by about 25 basis points. In contrast to the previous shock, however, this time much of the GDP 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 GDP 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 GDP gap down to that of the natural GDP gap (a 19 basis point 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 GDP gap, and in general results in excessive GDP gap variation. In order to stabilize the GDP 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 GDP gap. From the point of view of rule (10), in response to a negative oil technology shock that 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

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

[21] 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.

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.[22]

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 (30) 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 about 2.6 percentage points. By (36) the effective demand for OPEC oil becomes less price-elastic, which implies that the profit-maximizing oil price increases by about 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 about 0.15%), coupled with the constancy of the efficient level of output, translates into a fall (that is, widening) of the natural GDP gap by 15 basis points.

The actual allocation for this shock almost coincides with the natural one. The GDP 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 GDP 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 GDP gap in this case would have to come at the cost of increasing inflation. Hence, with respect to this shock, optimal monetary policy would involve a welfare-relevant trade-off between inflation and GDP 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 GDP gap stabilization.

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).

[22] 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.

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 basis point interest rate cut, US output (+0.25%) and inflation (+45 bp) both rise 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 GDP 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 GDP 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 GDP 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 GDP 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 GDP 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 and price stickiness prevent actual output from falling sufficiently. As we saw in section 4.2, a typical negative oil technology shock that 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 point increase in the GDP gap (and a 20 bp rise in inflation). If the central bank were to offset completely the effect of the shock on the GDP 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 point decrease in the GDP gap. Therefore, if the central bank wants to offset completely the effect of the shock on the GDP gap, it would have to lower the interest rate by about 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 GDP 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 GDP 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 GDP 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 that reacts to inflation only.

Unlike inflation, though, the output gap is an unobservable variable, making a rule that 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* that 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 that 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 calibration of the shock processes.

In particular, under our baseline calibration, US technology shocks account for about 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 about 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. 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 basis points) is due to fluctuations in the natural output gap (std 81 bp). Indeed, the correlation between these two output gap measures is about 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) that targets only inflation misses on the opportunity to stabilize the welfare-relevant output gap by countering 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. 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 (44) 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 that 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 about 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.[23]

[23] 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.

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 that raises the oil price by 10% is an increase in inflation by 2 percentage points—a response that 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 that raises the oil price by the same 10%, US output (and the output gap) falls by 4% (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 that 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 temporarily boosts 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, the unconditional 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.

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 specific value of 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 about $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 that raises the oil price by 10%, the nominal interest rate increases by about 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 about 50 basis points (contrary to the output gap *narrowing* by about 25 bp under the benchmark rule). And in response to a negative fringe shock that raises the oil price by 10%, output falls by 1.5% that 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 about 140 basis points. Therefore, this policy is clearly destabilizing, throwing the economy into an unnecessary recession in response to oil sector shocks that significantly raise 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 about 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 that 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 Equilibrium Conditions for a Given Oil Supply

7.1.1 Optimality conditions

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

$$C_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} C_t \tag{45}$$

$$C_t L_t^{\psi} = w_t \tag{46}$$

$$1 = \beta R_t E_t \left[\frac{C_t}{C_{t+1}} \frac{P_t}{P_{t+1}}\right]. \tag{47}$$

Condition (45) states that the relative demand for good i is inversely related to its relative price. Equation (46) is a standard labor supply curve equating the marginal rate of substitution between consumption and leisure to the real wage; and (47) is a standard consumption Euler equation.

Cost minimization by final goods firms implies

$$w_t L_t(i) = \alpha_1 mc_t Q_t(i) \tag{48}$$

$$r_t K_t(i) = \alpha_2 mc_t Q_t(i) \tag{49}$$

$$p_{ot} O_t(i) = (1 - \alpha_1 - \alpha_2) mc_t Q_t(i) \tag{50}$$

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

$$mc_t = \frac{w_t^{\alpha_1} r_t^{\alpha_2} p_{ot}^{1-\alpha_1-\alpha_2}}{A_t \alpha_1^{\alpha_1} \alpha_2^{\alpha_2} (1 - \alpha_1 - \alpha_2)^{1-\alpha_1-\alpha_2}}. \tag{51}$$

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

$$p_t^* \equiv \frac{P_t^*(i)}{P_t} = \frac{N_t}{D_t}, \tag{52}$$

where N_t and D_t are governed by

$$D_t = \frac{Q_t}{C_t} + \beta\theta E_t \left[\Pi_{t+1}^{\epsilon-1} D_{t+1}\right] \tag{53}$$

$$N_t = \mu mc_t \frac{Q_t}{C_t} + \beta\theta E_t \left[\Pi_{t+1}^{\epsilon} N_{t+1}\right] \tag{54}$$

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

$$P_t^{1-\epsilon} = \theta P_{t-1}^{1-\epsilon} + (1-\theta) P_t^{\star 1-\epsilon} \tag{55}$$

which implies

$$1 = \theta \Pi_t^{\epsilon-1} + (1-\theta) p_t^{\star 1-\epsilon}. \tag{56}$$

Denoting the relative price dispersion by

$$\Delta_t \equiv \int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} di, \tag{57}$$

one can derive a law of motion for this measure as

$$\Delta_t = \theta \Pi_t^{\epsilon} \Delta_{t-1} + (1-\theta) p_t^{\star -\epsilon}. \tag{58}$$

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.

7.1.2 Aggregation

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

$$L_t = \int_0^1 L_t(i) di \tag{59}$$

$$K_{dt} = \int_0^1 K_t(i) di \tag{60}$$

$$O_{dt} = \int_0^1 O_t(i) di \tag{61}$$

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

$$Q_t = \left[\int_0^1 Q_t(i)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}. \tag{62}$$

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,

$$p_{ot} O_{dt} = (1-\alpha_1-\alpha_2) mc_t Q_t \Delta_t \tag{63}$$

$$w_t L_t = \alpha_1 mc_t Q_t \Delta_t \tag{64}$$

$$r_t K_{dt} = \alpha_2 mc_t Q_t \Delta_t, \tag{65}$$

where aggregate output satisfies

$$Q_t = \frac{A_t}{\Delta_t} L_t^{\alpha_1} K_{dt}^{\alpha_2} O_{dt}^{1-\alpha_1-\alpha_2}. \tag{66}$$

Notice in particular the distortionary effect of aggregate price dispersion in (66), 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,

$$\frac{\Pi_t^f}{P_t} = Q_t - p_{ot} O_{dt} - w_t L_t - r_t \bar{K}. \tag{67}$$

7.1.3 Market clearing

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

$$B_t = 0 \tag{68}$$

$$K_{dt} = \bar{K} = 1 \tag{69}$$

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

$$C_t = w_t L_t + r_t \bar{K} + \frac{\Pi_t^f}{P_t}. \tag{70}$$

Substituting aggregate real profits from (67) in the above equation yields,

$$C_t = Q_t - p_{ot} O_{dt}. \tag{71}$$

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:

$$O_{dt} = O_t + X_t. \tag{72}$$

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

$$\hat{C}_t = p_{ot} X_t - \hat{I}_t. \tag{73}$$

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

$$Q_t = C_t + \tilde{C}_t + \tilde{I}_t + \hat{C}_t + \hat{I}_t, \tag{74}$$

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

7.2 The Dominant Oil Exporter's Problem

We assume that OPEC solves a Ramsey-type problem. Namely, it seeks 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,

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \log \left[p_{ot} O_t - O_t / Z_t \right] \tag{75}$$

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

$$X_t = \Omega_t p_{ot} Z_t, \tag{76}$$

of households,

$$w_t = C_t L_t^{\psi} \tag{77}$$

$$1 = \beta R_t E_t \left[\frac{C_t}{C_{t+1}} \frac{P_t}{P_{t+1}} \right], \tag{78}$$

and final goods firms in the oil-importing country,

$$D_t = \frac{Q_t}{C_t} + \beta \theta E_t \left[\Pi_{t+1}^{\epsilon-1} D_{t+1} \right] \tag{79}$$

$$N_t = \mu m c_t \frac{Q_t}{C_t} + \beta \theta E_t \left[\Pi_{t+1}^{\epsilon} N_{t+1} \right] \tag{80}$$

$$1 = \theta \Pi_t^{\epsilon-1} + (1-\theta) \left(\frac{N_t}{D_t} \right)^{1-\epsilon} \tag{81}$$

$$\Delta_t = \theta \Pi_t^{\epsilon} \Delta_{t-1} + (1-\theta) \left(\frac{N_t}{D_t} \right)^{-\epsilon} \tag{82}$$

$$p_{ot} = (1 - \alpha_1 - \alpha_2) m c_t Q_t \Delta_t / \left(O_t + X_t \right) \tag{83}$$

$$L_t = \alpha_1 m c_t Q_t \Delta_t / w_t \tag{84}$$

$$Q_t = \frac{A_t}{\Delta_t} L_t^{\alpha_1} \bar{K}_t^{\alpha_2} \left(O_t + X_t \right)^{1-\alpha_1-\alpha_2}, \tag{85}$$

the rule followed by the monetary authority,

$$\frac{R_t}{\bar{R}} = e^{r_t} \left(\frac{R_{t-1}}{\bar{R}} \right)^{\phi_R} \left(\frac{\Pi_t}{\bar{\Pi}} \right)^{\phi_\pi} \left(\frac{p_{ot}}{p_{ot-1}} \right)^{\phi_o}, \tag{86}$$

and the global resource constraint,

$$C_t = Q_t - p_{ot} \left(O_t + X_t \right). \tag{87}$$

We assume throughout that OPEC can commit to the optimal policy rule that brings about the equilibrium which maximizes expression (75) 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.

7.3 First order conditions of OPEC's problem

Let $s_o \equiv 1-\alpha_1-\alpha_2$ denote the share of oil in GDP. The following are the first order conditions of problem solved by the dominant oil exporter:

$$
\begin{aligned}
0 &= 1/O_t-(\lambda_{1t}+\lambda_{7t})p_{ot}+\lambda_{9t}s_o\frac{Q_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}+\lambda_{10t}L_t^{\psi}\\
&\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] && (C_t)\\
0 &= \lambda_{1t}+\lambda_{3t}+\lambda_{4t}\mu mc_t+\lambda_{7t}s_o mc_t\Delta_t-\lambda_{8t}\alpha mc_t\Delta_t-\lambda_{9t}\Delta_t && (Q_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 Q_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}s_o\frac{Q_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}s_o mc_t Q_t-\lambda_{8t}\alpha_1 mc_t Q_t-\lambda_{9t}Q_t && (\Delta_t)\\
0 &= \lambda_{4t}\mu Q_t+\lambda_{7t}(1-\alpha_1-\alpha_2)Q_t\Delta_t-\lambda_{8t}\alpha_1 Q_t\Delta_t && (mc_t)\\
0 &= \lambda_{2t}\beta E_t\left[\frac{C_t}{C_{t+1}\Pi_{t+1}}\right]-\lambda_{11t} && (R_t)\\
&\quad +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]\\
0 &= \lambda_{8t}L_t-\lambda_{10t} && (w_t)
\end{aligned}
$$

7.4 GDP 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 production gap $\tilde{q}_t$ as the (log) difference between actual production Q_t and its efficient level Q_t^e.

From the final-goods production function (66) and the oil share condition (23), we obtain the following two equations

$$\begin{aligned}\frac{\Delta_t Q_t}{Q_t^e} &= \left(\frac{L_t}{\bar{L}}\right)^{\alpha_1}\left(\frac{O_{dt}}{O_{dt}^e}\right)^{1-\alpha_1-\alpha_2}, \\ \frac{p_{ot}O_{dt}}{p_{ot}^e O_{dt}^e} &= \frac{mc_t\Delta_t}{\mu^{-1}}\frac{Q_t}{Q_t^e}.\end{aligned}$$

Eliminating the O_{dt}/O_{dt}^e from the above equations and taking log-deviations (denoted by hats) yields

$$\tilde{q}_t = \frac{\alpha_1}{\alpha_1+\alpha_2}\hat{l}_t + \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}\left(\hat{mc}_t+\hat{\Delta}_t\right) - \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}\left(\hat{p}_{ot}-\hat{p}_{ot}^e\right). \quad (88)$$

Using (83), (84), (77), and (87) it is easy to derive equilibrium labor as

$$L_t = \left[\frac{\alpha_1 mc_t\Delta_t}{1-(1-\alpha_1-\alpha_2)mc_t\Delta_t}\right]^{\frac{1}{1+\psi}}. \quad (89)$$

Taking a log-linear approximation of (89), we obtain,

$$(1+\psi)\hat{l}_t = \mu[\mu-1+\alpha_1+\alpha_2]^{-1}\hat{mc}_t.$$

Combining it with expression (88) above, dropping the constant and the higher-order term related to Δ_t, we obtain the following first-order approximation for the production gap,

$$\tilde{q}_t \simeq \kappa_{mc}^q\hat{mc}_t - \kappa_\nu\hat{\nu}_t, \quad (90)$$

where $\hat{\nu}_t = \hat{p}_{ot} - \hat{p}_{ot}^e$, and

$$\begin{aligned}\kappa_{mc}^q &\equiv \frac{\mu\alpha_1 + (1-\alpha_1-\alpha_2)(1+\psi)(\mu-1+\alpha_1+\alpha_2)}{(1+\psi)(\mu-1+\alpha_1+\alpha_2)(\alpha_1+\alpha_2)} \\ \kappa_\nu &\equiv \frac{1-\alpha_1-\alpha_2}{\alpha_1+\alpha_2}.\end{aligned}$$

To obtain the GDP gap $\tilde{y}_t$, defined as the log-difference between U.S. *value added* and its efficient level, we use the condition

$$Y_t = C_t = [1-(1-\alpha_1-\alpha_2)mc_t\Delta_t]Q_t,$$

which implies

$$\tilde{y}_t = \tilde{q}_t - \frac{1-\alpha_1-\alpha_2}{\mu-1+\alpha_1+\alpha_2}\hat{mc}_t.$$

Combining the above expression with the production gap (90), we obtain

$$\tilde{y}_t = \kappa_{mc}\hat{mc}_t - \kappa_\nu\hat{\nu}_t,$$

where

$$\kappa_{mc} \equiv \kappa_{mc}^q - \frac{1-\alpha_1-\alpha_2}{\mu-1+\alpha_1+\alpha_2} = \frac{\mu\alpha_1 + (1-\alpha_1-\alpha_2)(1+\psi)(\mu-1)}{(1+\psi)(\mu-1+\alpha_1+\alpha_2)(\alpha_1+\alpha_2)}.$$

7.5 Proof of proposition 3

With exogenous or competitive oil price, $p^e_{ot} = Z_t^{-1}$, the model can be written as follows: The production function is given by

$$Q_t = A_t L_t^{\alpha_1} \bar{K}^{\alpha_2} O_{dt}^{1-\alpha_1-\alpha_2} / \Delta_t. \tag{91}$$

Combining (24) with (46) we obtain

$$C_t L_t^{1+\psi} = \alpha_1 mc_t Q_t \Delta_t. \tag{92}$$

And combining (23) and (92) yields

$$p^e_{ot} O_{dt} = \frac{1-\alpha_1-\alpha_2}{\alpha_1} C_t L_t^{1+\psi}. \tag{93}$$

Resource constraint,

$$C_t = Q_t - p^e_{ot} O_{dt}. \tag{94}$$

The above four equations, together with (79), (80), (81), (82), describe fully the behavior of the private sector. A benevolent monetary policy maker who wants to maximize the welfare of the representative US household would solve the following Lagrangian:

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

System of first-order conditions:

$$1/C_t - \lambda_{1t} + \frac{p^e_{ot} O_{dt}}{C_t} \lambda_{2t} - L_t^{1+\psi} \lambda_{4t} - \lambda_{5t} Q_t / C_t - \lambda_{6t} \mu mc_t Q_t / C_t = 0 \tag{C_t}$$

$$-L_t^{\psi} + (1+\psi)\lambda_{2t} \frac{p^e_{ot} O_{dt}}{L_t} + \alpha_1 \lambda_{3t} Q_t / L_t - (1+\psi) C_t L_t^{\psi} \lambda_{4t} = 0 \tag{L_t}$$

$$p^e_{ot} O_{dt} (\lambda_{1t} + \lambda_{2t}) - (1-\alpha_1-\alpha_2) Q_t \lambda_{3t} = 0 \tag{O_{dt}}$$

$$\lambda_{1t} - \lambda_{3t} + \alpha_1 mc_t \Delta_t \lambda_{4t} + \lambda_{5t} + \mu mc_t \lambda_{6t} = 0 \tag{Q_t}$$

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

$$\alpha_1 mc_t Q_t \lambda_{4t} + \lambda_{8t+1} \beta \theta \Pi_{t+1}^{\epsilon} - \lambda_{8t} - \frac{Q_t}{\Delta_t} \lambda_{3t} = 0 \quad (\Delta_t)$$

$$\lambda_{5t-1} \theta C_{t-1} \Pi_t^{\epsilon-1} - C_t \lambda_{5t} - \lambda_{7t}(1-\theta)(1-\epsilon) N_t^{1-\epsilon} D_t^{\epsilon-2} = 0 \quad (D_t)$$

$$\lambda_{6t-1} \theta C_{t-1} \Pi_t^{\epsilon} - C_t \lambda_{6t} + \lambda_{7t}(1-\theta)(1-\epsilon) N_t^{-\epsilon} D_t^{\epsilon-1} = 0 \quad (N_t)$$

$$\lambda_{5t-1}(\epsilon-1)\Pi_t^{\epsilon-2} D_t C_{t-1} + \lambda_{6t-1} \epsilon \Pi_t^{\epsilon-1} N_t C_{t-1} + \lambda_{7t}(\epsilon-1)\Pi_t^{\epsilon-2} + \quad (\Pi_t)$$

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

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

From (81), our guess $\Pi_t = 1$ implies that $N_t = D_t$. This, from (79) and (80) yields $mc_t = \mu^{-1}$ (the price markup is constant). In addition, from (82) and starting with $\Delta_{-1} = 0$, we have $\Delta_t = 1$ (there is no price dispersion). Substituting $\Delta_t = 1$ and $mc_t = \mu^{-1}$ in (89) we obtain

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

which is equal to the efficient level of labor effort established in section 2.5. Rewriting (23) using the above results,

$$p_{ot}^e O_{dt} = (1-\alpha_1-\alpha_2) Q_t / \mu,$$

and substituting O_{dt} from above equation into (91), we obtain

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

which is equal to the efficient level of output derived in section 2.5. Moreover,

$$C_t = \left[1 - (1-\alpha_1-\alpha_2)\mu^{-1} \right] Q_t = C_t^e$$

corresponds to the efficient level of consumption. All other real endogenous variables can be expressed similarly in terms of $Q_t = Q_t^e$. Thus, a policy of full price stability replicates the real allocation attained in the efficient (first-best) equilibrium.

Using the above, we can rewrite the conditions that have to be satisfied by the Lagrange multipliers as follows:

$$
\begin{aligned}
\lambda_{3t} &= \frac{1}{(\alpha_1+\alpha_2)Q_t} \\
\lambda_{5t} &= \lambda_{3t} - \lambda_{1t} \\
\lambda_{6t} &= -\lambda_{4t}\alpha_1/\mu \\
p^e_{ot}O_{dt}\left(\lambda_{2t} - \frac{\alpha_1}{1-\alpha_1-\alpha_2}\lambda_{4t}\right) &= \frac{\bar{L}^{1+\psi}}{(1+\psi)} - \frac{\alpha_1}{(1+\psi)(\alpha_1+\alpha_2)} \\
\alpha_1 Q_t\lambda_{4t}/\mu + \lambda_{8t+1}\beta\theta - \lambda_{8t} &= \frac{1}{\alpha_1+\alpha_2} \\
\lambda_{5t-1}\theta C_{t-1} - C_t\lambda_{5t} &= \lambda_{7t}(1-\theta)(1-\epsilon)/D \\
\lambda_{6t-1}\theta C_{t-1} - C_t\lambda_{6t} &= -\lambda_{7t}(1-\theta)(1-\epsilon)/D \\
\lambda_{5t-1}(\epsilon-1)C_{t-1} + \lambda_{6t-1}\epsilon C_{t-1} &= \lambda_{7t}(1-\epsilon)/D
\end{aligned}
$$

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

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

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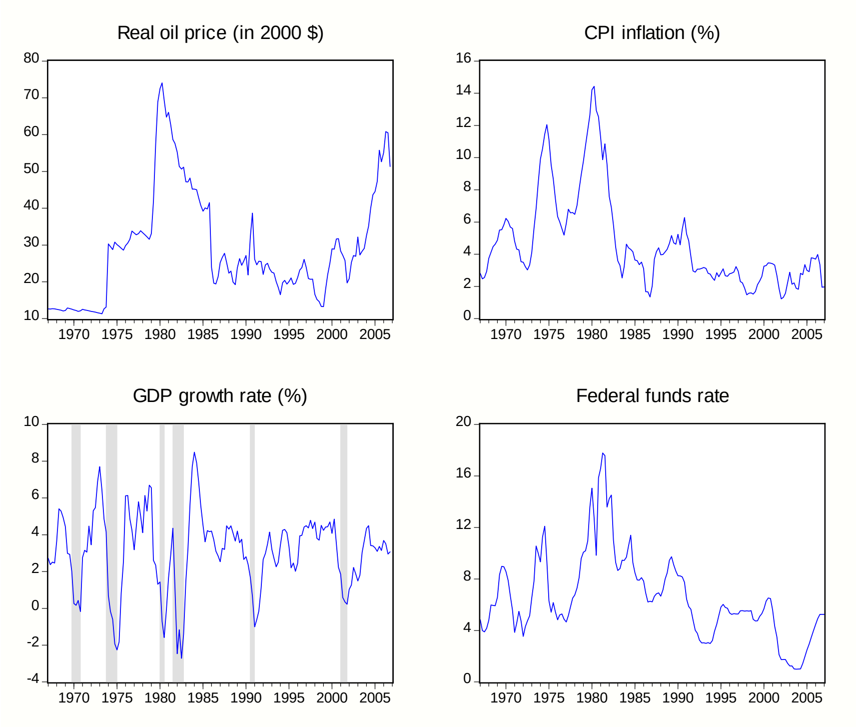

Figure 1: Price of oil, inflation, growth and Fed rate

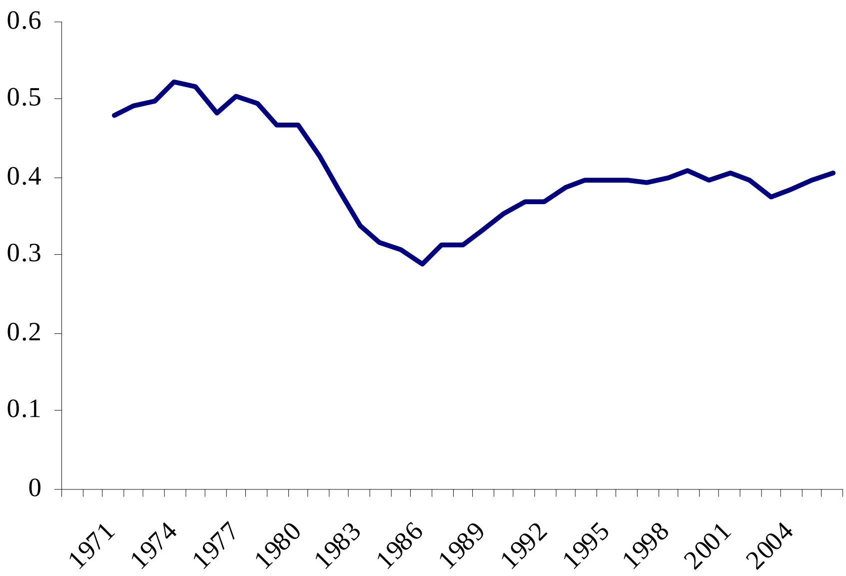

Figure 2: OPEC's world market share

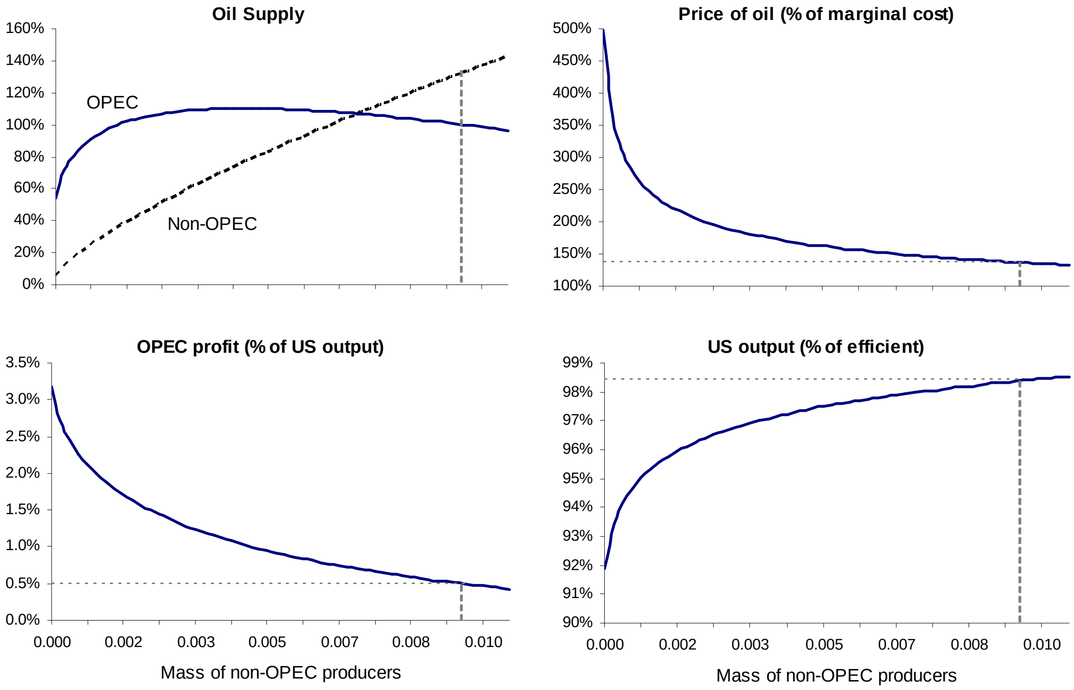

Figure 3: Comparative statics: mass of non-OPEC producers ($\bar{\Omega}$)

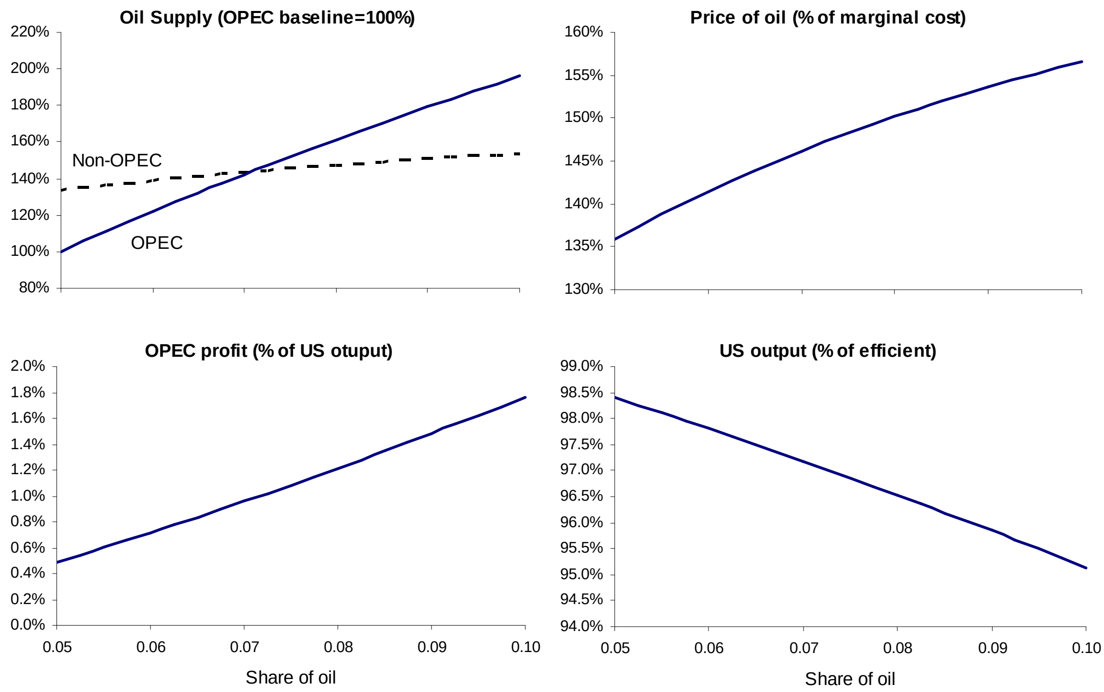

Figure 4: Comparative statics: elasticity of oil in production (keeping the mass of non-OPEC constant)

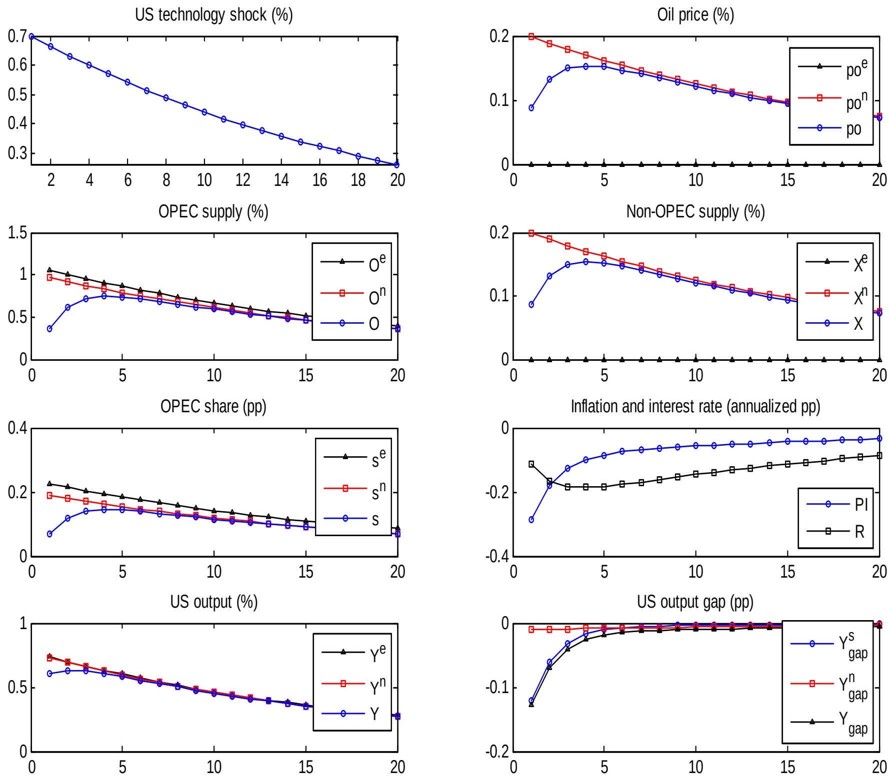

Figure 5: Responses to a positive US TFP shock

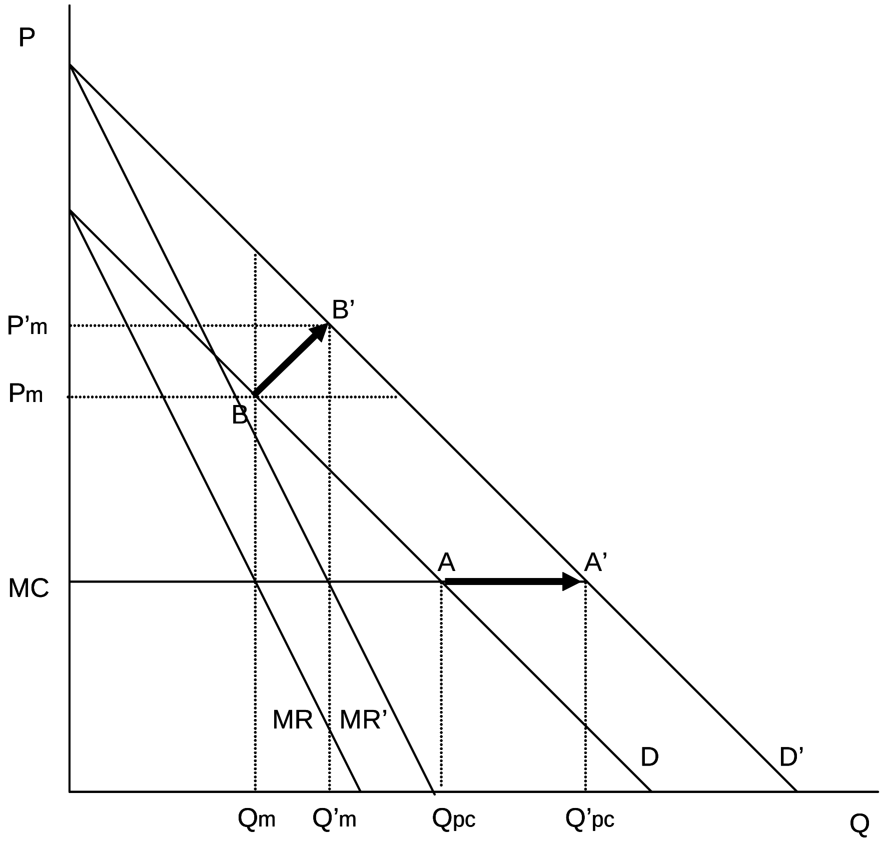

Figure 6: Competitive and monopoly response to a positive demand shock.

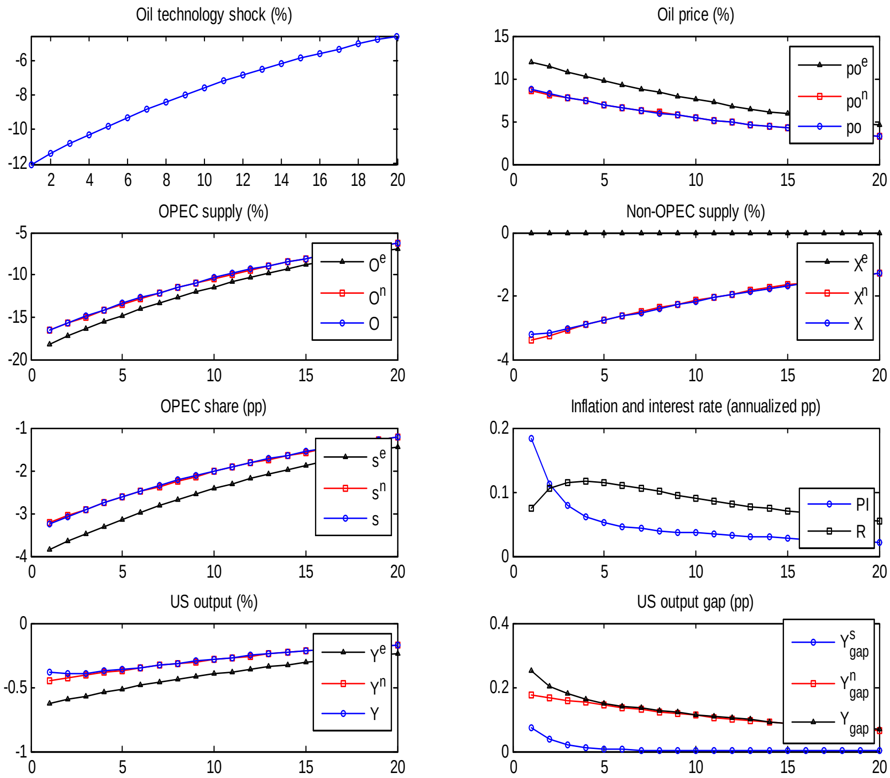

Figure 7: Responses to a negative oil technology shock

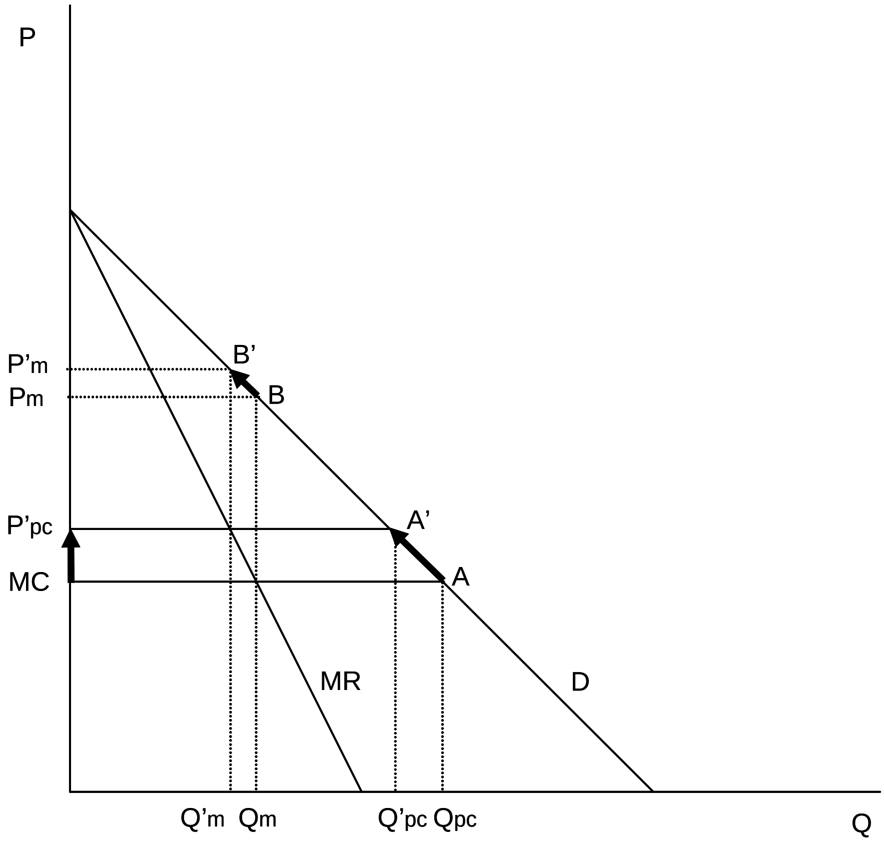

Figure 8: Competitive and monopoly response to an oil technology shock.

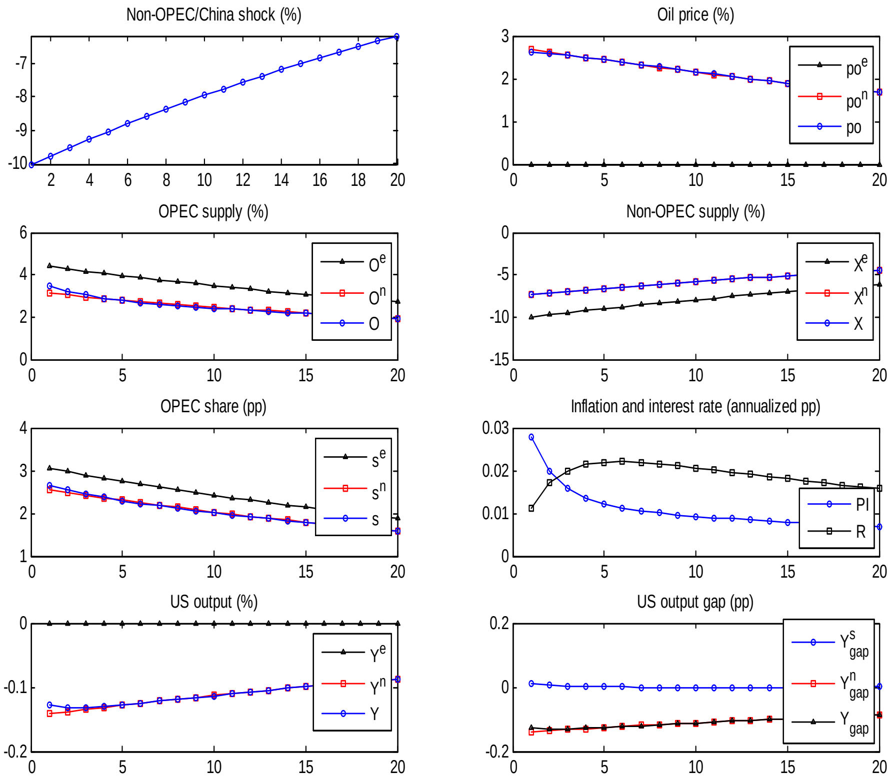

Figure 9: Responses to a negative fringe capacity shock

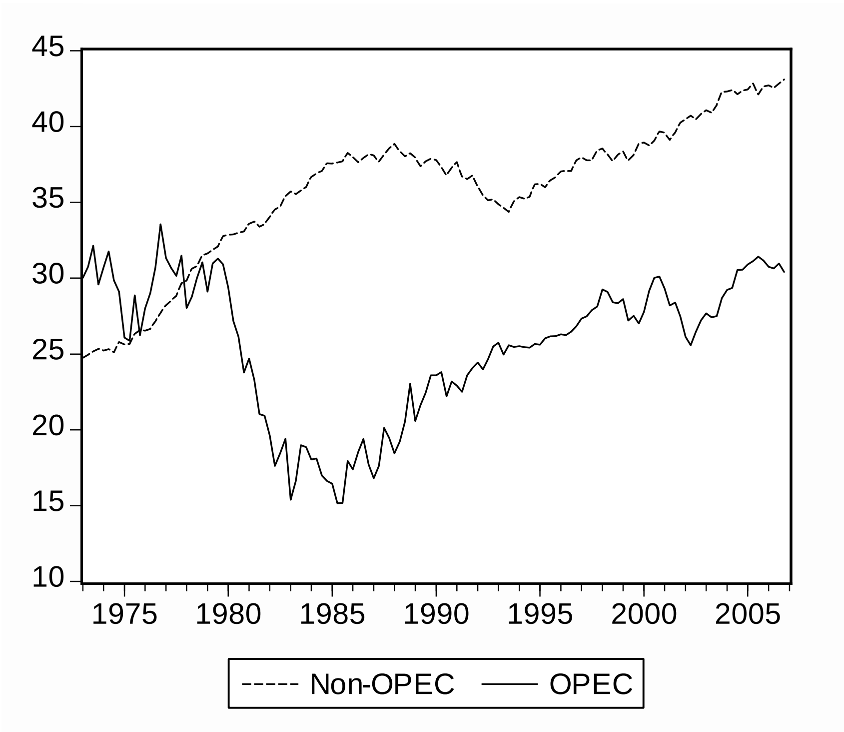

Figure 10: OPEC and non-OPEC oil supply (million barrels per day)

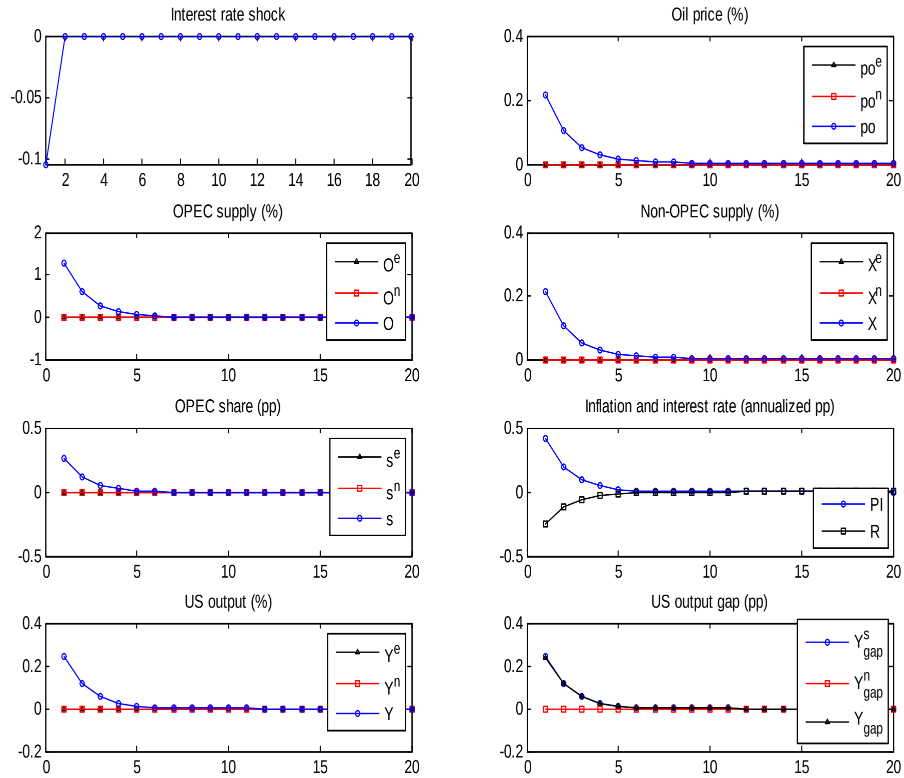

Figure 11: Responses to a negative interest rate shock