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Anton Nakov and Galo Nuño

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(**) Anton Nakov is at Banco de España, División de Investigación, Estudios Monetarios y Financieros, Alcalá 48, 28014 Madrid. Galo Nuño is at Banco de España, Economía y Asuntos Internacionales, Alcalá 48, 28014 Madrid.

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Abstract

Saudi Arabia is the largest player in the world oil market. It maintains ample spare capacity, restricts investment in developing reserves, and its output is negatively correlated with other OPEC producers. While this behavior does not fit into the perfect competition paradigm, we show that it can be rationalized as that of a dominant producer with competitive fringe. We build a quantitative general equilibrium model along these lines which is capable of matching the historical volatility of the oil price, competitive and non-competitive oil output, and of generating the observed comovement among the oil price, oil quantities, and U.S. GDP.

We use our framework to answer questions on which available models are silent: (1) What are the proximate determinants of the oil price and how do they vary over the cycle? (2) How large are oil profits and what losses do they imply for oil-importers? (3) What do different fundamental shocks imply for the comovement of oil prices and GDP? (4) What are the general equilibrium effects of taxes on oil consumption or oil production? We find, in particular, that the existence of an oil production distortion does not necessarily justify an oil consumption tax different from zero.

Keywords: Oil price, oil shocks, dominant firm, competitive fringe, Pigovian tax.

JEL classification: D43, E32, E62, Q43.

1 Introduction

Saudi Arabia is the largest player in the global oil market: it produces more than a tenth of the world's oil output and owns a quarter of the world's proven oil reserves. The Kingdom is also a principal OPEC member, playing a central role in the cartel's decision-making. Indeed, authors such as Mabro (1975) and Alhajji and Huettner (2000) declare that "*OPEC is Saudi Arabia*", while Adelman (1995) claims that "*the Saudis have acted as what they are: the leading firm in the world oil market*".

The behavior of Saudi Arabia can hardly be described as competitive. It maintains ample spare capacity, restricts investment in developing available reserves, and its output is negatively correlated with other OPEC producers (Smith, 2009). Furthermore, Saudi oil output has been highly volatile compared to other major producers, even though the Kingdom itself has witnessed few domestic shocks affecting oil production directly. In section 2 we report evidence supporting the notion that Saudi Arabia has behaved in a non-competitive way, and that the world oil market does not fit well into the perfect competition paradigm.

One of the goals of this paper is to show that one can rationalize the behavior of Saudi Arabia as that of a dominant producer with competitive fringe. Similar to Nakov and Pescatori (2010a), the dominant producer acts as a monopolist supplier of the residual oil demand, picking profit maximizing points on its residual demand curve. We add further realism by allowing for capital accumulation by oil producers subject to investment adjustment costs. Different from Nakov and Pescatori where oil is used as an input in production, in the present model it is used for consumption by households, whose demand for oil is only weakly sensitive to changes in the oil price.[1]

These additional features allow us to achieve a better fit of the model to the actual data. Namely, we are able to match the volatility of key variables such as the oil price, competitive and non-competitive oil supply, as well as to account for the comovement among the oil price, oil quantities, and GDP observed in historical episodes. We achieve this improved fit with only two standard shocks to TFP – of oil importers and of competitive fringe oil producers. In addition, we derive new analytical results linking the cost advantage and the capital utilization rate of the dominant oil producer to the conditions for its profitable existence.

Our general equilibrium model allows us to answer interesting questions on which most available models are silent, such as: (1) What are the proximate determinants of the oil price and how do they vary over the cycle? (2) How large are oil profits and what losses do they imply for oil-importers? (3) What do different fundamental shocks imply for the comovement of oil prices and GDP? (4) What are the general equilibrium effects of taxes on oil consumption or oil production?

Our findings can be summarized as follows. A dominant oil producer may persist in the long run as long as it enjoys a permanent cost advantage. In equilibrium, the oil price is determined by the (higher) marginal cost of competitive fringe producers, who collectively limit the market power of the dominant firm. The fact that the dominant producer maintains spare capacity even while enjoying a permanent productivity advantage imposes a distortion on oil-importing countries in terms of lower oil consumption and GDP. We show that a positive oil consumption tax may not necessarily improve welfare, even if it results in higher GDP for oil importers. In particular, we find that in the case of constant returns to scale in oil production, the optimal oil consumption tax is zero while the oil market distortion can be mitigated effectively by subsidizing oil production. A positive oil consumption tax can be welfare improving in the case of decreasing returns to scale in oil production.

After a brief review of the related literature in the following paragraphs, in section 2 we document several historical facts pointing to the central role of Saudi Arabia in the oil market. In section 3 we lay out the model and calibrate it to fit the main data averages. In section 4 we derive results regarding the long-run behavior of oil prices, oil efficiency in importing countries, and the dominant producer's capacity utilization and price markup. In section 5 we analyze the dynamic properties of the model comparing it with the data in terms of volatilities and impulse-responses. In section 6 we simulate three possible future oil market scenarios. And in section 7 we analyze the general equilibrium effects of taxes on oil consumption and oil production. Section 8 concludes.

[1] Focusing on oil used for consumption is in part motivated by Kilian's (2008) emphasis on the importance of the response of consumer expenditure to energy price shocks.

1.1 Related literature

A long list of articles study the transmission of oil price shocks taking oil price changes as given exogenously, typically in the form of an exogenous AR(1) driving process (e.g. Kim and Loungani, 1992; Leduc and Sill, 2004; Carlstrom and Fuerst, 2005). Yet oil price shocks usually do not happen in isolation. Rather, like other relative price movements, they are triggered by deeper shocks to preferences, technology, and policy. In other words, the oil price is determined, jointly with the oil quantity produced and consumed, as an equilibrium outcome of the interaction of different market participants.

Indeed, starting with Barsky and Kilian (2002, 2004), and Kilian (2009), overwhelming evidence has been compiled against the assumption of exogenous oil prices and in support of the notion that the oil price is affected significantly by global economic conditions. This is important both from a positive point of view, as suggested by Kilian (2009), and it has important (monetary) policy implications, as demonstrated in a welfare-maximizing framework by Nakov and Pescatori (2010a,b).

Despite all this evidence, few general equilibrium models treat the oil price as endogenous, and even fewer determine endogenously both the oil price and the oil quantity. Recent exceptions include work by Leduc and Sill (2007), Bodenstein et. al. (2008, Section 6), and Campolmi (2008), in which the oil price is determined endogenously, while oil supply is given as an exogenous endowment. Going one step further, Elekdag et. al. (2008) endogenize also oil supply decisions, extending IMF's multi-country GEM model to include an oil-producing sector operating under monopolistic competition. Compared to their model, in which the market share of oil producers can vary only exogenously, we propose a setup in which the market share of the dominant oil producer varies endogenously in response to the fundamental shocks.

Perhaps the currently most popular equilibrium model of the oil-macroeconomy nexus, that of Backus and Crucini (2000), postulates oil output as the sum of two terms: an endogenous term linked to economic activity (representing competitive oil supply) and an exogenous term, or "oil supply shock" (representing unpredictable OPEC supply changes). Arguably, this framework provides a reasonable first approximation for studying the transmission of oil shocks, allowing greater realism and complexity on other dimensions; yet it is not especially suited to explaining salient features of the oil market itself. For example, OPEC supply is taken as exogenously given, and hence neither explained, nor allowed to be affected by the decisions of other market participants. Rather than assuming that non-competitive oil supply is exogenous, we model it as the profit-maximizing response of a dominant firm with competitive fringe.

2 A Closer Look at the Oil Market

To fix some ideas about the oil industry we take a closer look at three-and-a-half decades of oil market data. What emerges is a picture of a granular oil industry which is quite different from the standard perfect competition benchmark.

A first obvious discrepancy is the sheer size of the players in this market. To take an example, the combined output of five of the largest oil companies: Aramco (Saudi Arabia), NIOC (Iran), KPC (Kuwait), PDV (Venezuela), and INOC (Iraq), all of them 100% owned by OPEC member states, accounts for as much as a third of global oil production. Moreover, the same five companies control more than half of the world's "proven reserves", known oil deposits which can be economically extracted at prevailing prices using existing technology[2]. Such a high degree of concentration of production and reserves in the hands of a small number of players is in sharp contrast with the stylized view of a perfectly competitive market supplied by a large number of tiny price-taking firms.

Focusing on Saudi Aramco, a company which alone accounts for more than a tenth of global oil production and a fifth of total proven reserves, it is hard to square its activities with a profit-maximizing price-taking framework. In particular, even though the company has the lowest marginal costs and controls the world's largest proven reserves, it maintains ample spare capacity and restricts investment in developing available reserves (Smith, 2009). Estimates of the marginal cost of oil production of Aramco amount to less than $5 per barrel (Smith, 2009), while its spare capacity in 2009 stood at 25%[3]. While underutilizing installed capital and underinvesting in new capital makes little sense for a profit maximizing, price-taking firm, it is possible to rationalize these two pieces of strategy for a firm which

[2]Source: *Statistical Review of World Energy,* British Petroleum (2008)

[3]Source: *World Energy Outlook,* International Energy Agency (2009)

is capable of affecting the oil price. In particular, limiting capacity growth is likely to raise the average oil price, while "mothballing" existing production capacity allows for a swift reaction to demand and supply shocks by adjusting output as necessary. In the following paragraphs we point to evidence for this type of behavior by looking at the historical volatility of Saudi oil supply in comparison to that of other important producers, as well as by studying particular historical episodes of oil market disruption.

2.1 Production and spare capacity

In Table 1 we document several features of Saudi Aramco that set it apart from other suppliers in the oil market. First, Aramco is by far the largest oil company in the world by production (10 million bpd) and by proven reserves (265 billion barrels), with a global market share of about 12%. The second largest oil company, Iran's NIOC, produces less than half of Aramco's output (4.4 million bpd) and owns about half of the proven reserves (138 billion barrels). The third largest company, Mexico's Pemex, produces around a third of Aramco's output and its proven reserves are almost exhausted. Other large oil companies produce even less: for example Russia's oil companies are much smaller, with the largest one, Rosneft, producing only about a fifth of Aramco's output.

Second, Saudi Arabia's oil production has been extremely volatile (see figure 1). Its monthly standard deviation (83%) has been well above the one of Russia (16%) or the United States (27%). Although the output of other large OPEC producers such as Iran, Iraq, or Kuwait, has been quite volatile, unlike Saudi Arabia these other countries experienced war, strikes, and political turmoil that directly affected oil production. Compared to these countries, Saudi Arabia was an island of stability: according to the U.S. Energy Information Administration's "Official oil market chronology", the only instances when Saudi oil production was directly affected by exogenous events were a fire at the Abqaiq facilities which halved production in 1977, the "tanker war" in 1984, when several Saudi tankers were destroyed, and the attacks in 1991 by Iraqi missiles during the first Gulf war. Apart from these singular episodes, changes in Saudi oil production were the result of business decisions, and not the consequence of exogenous disruptions to their production capabilities.

Third, Saudi Arabia is the only producer with significant spare capacity. According to the International Energy Agency (2009), Aramco's spare capacity in 2009 stands at 25% of oil supply. To put this in perspective, it is equivalent to the entire production of oil exporters such as Kuwait or Venezuela.

2.2 Four historical episodes

Here we briefly review four historical episodes of oil market disruption, placing a focus on the role played by Saudi Arabia. Two of the events can roughly be characterized as "oil supply shocks", the Iran revolution in 1978-79 and the Gulf War in 1991, and the other two as "oil demand shocks", the dotcom bust in 2000-1 and the subprime crises in 2008-9.

Iranian revolution. After numerous strikes on Iranian oil fields, Iran's oil production fell from 6 mbd in September 1978 to 0.7 mbd in January 1979. At the same time Saudi Arabia raised its output from 8.3 mbd to 10.4 mbd in December 1978, a 25% increase in production in only 3 months. During this period other major producers such as the USSR and the USA did not raise their output. The posted oil price more than doubled from $14.8 at the beginning of the crisis to $32.5 by the end of 1979.

First Gulf war. On 2 August 1990 Iraqi forces invaded Kuwait. During the war, combined Iraqi and Kuwaiti production fell from 5.3 mbd in July 1990 to virtually zero in February 1991. Because of the trade embargo on Iraq and the mayhem on Kuwaiti oil fields, the oil production of the two countries remained minimal for some time after the end of the conflict. This fall in oil supply was partially offset by a jump in Saudi Arabia's output, which rose from 5.4 mbd in July 1990 to 8.4 mbd by the end of the year (a 56% increase in five months). Other major oil producers did not increase their production significantly: from July 1990 to July 1991, Iran and the USA increased their output by only 0.2 mbd, while the Soviet Union reduced its production.[4]

Dotcom bust. Following the IT boom of the late 1990s, the Nasdaq started falling abruptly in 2000, leading to a recession in March 2001. Along with the contraction, world oil production leveled out in

[4] A similar pattern of collapsing Iraqi oil supply accompanied by a sizable increase in Saudi Arabia's oil output can be seen also in the Second Gulf war of 2003.

November 2000 while oil prices remained in the \$27-28 range for a few months. Saudi Arabia began reducing its output by 0.5 mbd, a 6% reduction, even before any significant price decline. In the same period Russia and Iran reduced their output each by 1% while the US kept its production unchanged. By the end of the official U.S. recession in November 2001, world oil supply had fallen by 1.2 mbd compared to December 2000, of which 1.1 mbd was the cutback of Saudi supply.

Subprime crisis. Booming world trade and economic growth since 2002 were accompanied by an increase in the demand for commodities by Asian economies, notably China. Oil prices rose steeply reaching \$140 per barrel in July 2008. Once the subprime financial crisis hit the real sector, oil prices started a rapid fall, collapsing to \$40 per barrel in February 2009. In an extraordinary meeting in November 2008, OPEC decided to reduce its output by 4.2 mbd from its September level. By January, world oil supply had fallen 3.2 mbd, of which 3.1 mbd were OPEC production cuts. Of this, 1.5 mbd was the reduction of Saudi output, a 16% cut. Other large OPEC producers such as Iran, Iraq, or Kuwait reduced their output by around 0.2 mbd each.

3 The Model

We model the global economy as comprising three regions: one oil-importing and two oil-exporting. The oil-importing region imports oil for use in consumption, and employs labor in the production of final goods, part of which are consumed domestically, with the rest exported to the two oil-producing regions. Oil is a homogeneous commodity supplied by a dominant oil producer ("Saudi Aramco") and competitive oil producers ("the fringe"). The fringe producers take the oil price as given when choosing their production level. The dominant producer faces a downward sloping "residual demand" curve and picks the profit-maximizing point on that curve at each point in time. Oil exporters produce oil only and their revenue is recirculated to the oil-importing region in the form of demand for final consumption and investment goods. We assume financial autarky and abstract from nominal factors[5].

3.1 Oil-importing region

A representative household has a period utility function which depends on consumption, C_t, oil O_t, and labor L_t, and takes the form

$$U(C,O,L) = \log(C) + \nu_t O^{1-\eta}/(1-\eta) - L^{1+\psi}/(1+\psi). \tag{1}$$

As we explain in section 4.1, we allow for a trend in ν_t to reflect secular features of the data, while ensuring the existence of a balanced growth path.

The household faces the period t budget constraint,

$$C_t + s_t O_t = w_t L_t + D_t \tag{2}$$

which equates income from labor, $W_t L_t$, and dividends from the ownership of firms, D_t, to outlays on consumption, C_t, and oil, $s_t O_t$. We assume that all oil must be consumed within the period of production.[6]

The household chooses C_t, O_t, and L_t, to maximize the expected present discounted sum of utility,

$$\max_{C_t,O_t,L_t} E_o \sum_{t=0}^{\infty} \beta^t U(C_t,O_t,L_t), \tag{3}$$

subject to the budget constraint (2).

Final goods are produced under perfect competition with labor only according to

$$Y_t = Z_t L_t^{\alpha} \tag{4}$$

with $\alpha < 1$; aggregate total factor productivity Z_t follows an AR(1) in log differences. That is, $g_t^z = \rho_z g_{t-1}^z + \varepsilon_t^z$, where $g_t^z \equiv \Delta \log(Z_t)$ and σ_z^2 is the variance of the innovation ε_t^z.

[5] Gillman and Nakov (forthcoming) focus on the likely monetary factors behind historical episodes of large oil price realignments.

[6] As Litzenberger and Rabinowitz (1995) point out, oil storage "above ground" is limited because of the high physical storage cost. Most of the oil "stored" above ground is oil in transit to refineries in pipelines or tankers. Relaxing this assumption to allow for some delay between production and consumption does not affect significantly our main results.

3.2 Oil-exporting regions

Modelling the oil industry as a dominant firm with competitive fringe dates back to Salant (1976).[7] 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 the model nests these two extreme special cases, our preferred calibration is one in which the dominant oil producer has an average marker share of 12%, intended to capture the role of Saudi Arabia in the oil market since 1973. For this intermediate case, the model is able to generate a negative correlation between Saudi Arabia's and fringe producers' supply, a common feature found in the data, especially in the 1980s and early 1990s.

Except for the difference in market power, the fringe producers and the dominant firm are modelled symmetrically. We will decorate variables corresponding to the competitive fringe by tildes, and variables belonging to the dominant firm by hats.

3.2.1 Competitive fringe producers

A representative household maximizes the present discounted flow of utility from consumption,

$$\max_{\tilde{C}_t,\tilde{I}_t} E_o \sum\nolimits_{t=0}^{\infty} \beta^t \log(\tilde{C}_t), \tag{5}$$

subject to the period budget constraint,

$$\tilde{C}_t + \tilde{I}_t = \tilde{r}_t^k \tilde{K}_{t-1} + \tilde{D}_t$$

where consumption, $\tilde{C}_t$, and investment, $\tilde{I}_t$, are both purchased from the oil-importing region, $\tilde{r}_t^k$ is the gross return on capital $\tilde{K}_t$ rented out by the household to oil firms, and $\tilde{D}_t$ are oil firm dividends rebated lump sum to the representative household. The household invests in capital according to,

$$\tilde{K}_t = (1-\delta)\,\tilde{K}_{t-1} + \left[1 - \chi(\tilde{I}_t/\tilde{I}_{t-1} - G^z)^2/2\right]\tilde{I}_t, \tag{6}$$

where δ is the depreciation rate, and $\chi > 0$ is an investment adjustment cost as in Christiano, Eichenbaum and Evans (2005). Lucca (2005) shows that this formulation of the adjustment cost function is equivalent, up to a first order approximation, to a time-to-build constraint.

There is a representative fringe firm, owned by the household, which maximizes period profits $\tilde{D}_t$,

$$\max_{\tilde{X}_t,\tilde{K}_{t-1}} \left(s_t\tilde{O}_t - \tilde{X}_t - \tilde{r}_t^k \tilde{K}_{t-1}\right),$$

subject to the production technology,

$$\tilde{O}_t = \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}}, \tag{7}$$

while *taking the oil price as given.* The firm buys the intermediate good $\tilde{X}_t$ from the oil-importing region, and rents the capital $\tilde{K}_t$ from the household. Total factor productivity $\tilde{Z}_t = \tilde{A}_t\tilde{Z}\exp(g^{\tilde{z}}t)$ follows an exogenous process with a secular trend component $\tilde{Z}\exp(g^{\tilde{z}}t)$, and a stationary AR(1) component $\tilde{A}_t$ with persistence $\rho_{\tilde{A}}$ and variance of the innovation $\sigma^2_{\tilde{A}}$.

3.2.2 Dominant oil producer

The dominant producer's economy has a structure symmetric to that of fringe producers (with hats replacing tildes). A single firm produces oil, $\hat{O}_t$, according to (7) using an imported intermediate good $\hat{X}_t$ and capital $\hat{K}_{t-1}$. Technology evolves deterministically according to $\hat{Z}_t = \hat{Z}\exp(g^{\hat{z}}t)$ (that is, we do not need a technology shock specific to the dominant firm). Capital is accumulated following (6) by purchasing $\hat{I}_t$ units of the investment good from the oil-importing region and the representative household receives a stream of log utility from consumption $\hat{C}_t$.

The substantial difference between the dominant producer and fringe producers is that the dominant producer has market power: it is aware of the fact that it faces a downward-sloping residual demand

[7] Almoguera and Herrera (2007), while finding only sporadic evidence of collusion among OPEC members, lend support to a model of Cournot competition among OPEC members operating alongside a competitive fringe of non-OPEC producers.

curve, in other words, that the equilibrium oil price depends on its supply decision. We assume that the dominant producer chooses a state-contingent plan of action which maximizes the expected present discounted utility of its representative household-owner, subject to the optimal *intratemporal* choices of households and firms of the oil-importing region, the competitive fringe producers, and the resource constraint. Appendix A contains the full set of optimality conditions of the oil-importing region and the competitive fringe that must be satisfied in equilibrium for any given strategy of the dominant oil producer.

After consecutive substitution we reduce the number of constraints down to the six equations listed below and we are left with eight decision variables. Four of these are variables which are under the direct control of the dominant producer (its consumption, investment, intermediate input and capital allocation), while the other four are variables which are proximate to its directly controlled variables (total oil supply and the oil price, intermediate good purchases by the fringe, and employment in the oil-importing region).

Thus, the decision problem of the dominant oil producer can be formulated compactly as follows,

$$\max_{\hat{C}_t,\hat{K}_t,\hat{I}_t,\hat{X}_t,\tilde{X}_t,s_t,O_t,L_t} E_o \sum_{t=0}^{\infty} \beta^t \log(\hat{C}_t)$$

subject to

$$\hat{C}_t = s_t \hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}} - \hat{I}_t - \hat{X}_t \tag{8}$$

$$\hat{K}_t = (1-\delta)\,\hat{K}_{t-1} + \left[1 - \chi(\hat{I}_t/\hat{I}_{t-1} - G^z)^2/2\right]\hat{I}_t, \tag{9}$$

$$s_t O_t^{\eta} = \nu_t \alpha Z_t L_t^{\alpha-1-\psi} \tag{10}$$

$$\tilde{X}_t = \tilde{\gamma} s_t \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}} \tag{11}$$

$$O_t = \hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}} + \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}} \tag{12}$$

$$s_t O_t^{\eta} = \nu_t Z_t L_t^{\alpha} - \nu_t s_t O_t. \tag{13}$$

Equilibrium is determined by the solution to the above problem. The complete model, including the first-order optimality conditions of the dominant oil producer, is given in Appendix B.

3.3 Calibration to data averages

The model is calibrated to monthly frequency. We begin by setting two trend parameters: namely, the steady-state growth rate of the final goods production technology g^z is chosen to match an average output growth of 3 percent per year. Consistent with the stationary market share of Saudi Arabia in the data, we impose equality between the steady-state growth rates of the dominant ($g^{\hat{z}}$) and the fringe ($g^{\tilde{z}}$) oil producers. Since oil production inputs grow at rate g^z, while oil technology grows at rate $g^{\tilde{z}}$, the sum of g^z and $g^{\tilde{z}}$ must match the average growth rate of total oil production (0.8 percent per year). The latter implies a value for $g^{\tilde{z}}$ of -2.2 percent per year.

Second, we set four parameters which are common in the RBC literature to their typical values. These include an annual time discount factor β of 0.99; labor share in the oil-importing country α of 0.67; annual capital depreciation rate δ of 10%; and unit Frisch labor supply elasticity.

Third, normalizing the initial level of productivity of fringe suppliers $\tilde{Z}$ to 1, we are left with five structural parameters affecting steady-state oil supply and demand ($\hat{Z}$, $\tilde{\gamma}$, $\hat{\gamma}$, η, ν). We set $\hat{Z}$ equal to 2 so that, other things equal, the dominant producer is twice as productive as fringe producers. The variable input share in fringe production $\tilde{\gamma}$ is set equal to 0.4, while the same parameter for the dominant producer $\hat{\gamma}$ is fixed at 0.5 (this difference enables us to match the higher output volatility of the dominant producer relative to the fringe). Parameter η is set to 21 consistent with estimates of the short-run price elasticity of oil demand about 0.05. Given the above choices, parameter ν is set such that the oil share in GDP (sO/C) is about 5 percent. Table 2 shows the fit of the model to five relevant data averages.

4 Secular Features of the Oil Market

4.1 Conditions for balanced growth

The model incorporates secular trends in the growth rate of final goods technology (Z_t), oil production technology ($\tilde{Z}_t$ and $\hat{Z}_t$), and oil efficiency (ν_t). In a steady-state with balanced growth, the ratio $s_t O_t / Y_t$ must remain constant over time. This implies that

Proposition 1 *The real price of oil grows at rate $-g^{\tilde{z}}$.*

Proof. Since O_t grows at rate $g^z + g^{\tilde{z}}$, while Y_t grows at rate g^z, for the ratio $s_t O_t / Y_t$ to remain stable, s_t should grow at a rate $-g^{\tilde{z}}$. ■

Given our parametrization, this implies that the real oil price should grow at an annual rate of 2.2 percent, which is consistent with the the average growth rate observed in the data.

The variable ν_t scales the utility of consumption of oil in terms of the utility of consumption of final goods. One of the first-order optimality conditions is the oil demand curve $\nu_t C_t = s_t O_t^{\eta}$. Assuming balanced growth requires that

Proposition 2 *Oil efficiency ν_t grows at rate $(\eta - 1)\left(g^z + g^{\tilde{z}}\right)$.*

Proof. Along the balanced growth path C_t grows at rate g^z while $s_t O_t^{\eta}$ grows at rate $\eta\left(g^z + g^{\tilde{z}}\right) - g^{\tilde{z}}$. Hence, along the balanced growth path ν_t must grow at rate $(\eta - 1)\left(g^z + g^{\tilde{z}}\right)$. ■

4.2 Oil price markup and permanent GDP loss

The dominant oil producer behaves as a monopolist supplier of the "residual" oil demand, that demand which cannot be satisfied by the competitive fringe at the going price. The dominant producer is thus able to extract a pure profit by picking a profit-maximizing point on the residual demand curve, where marginal revenue crosses his marginal cost. We can show that,

Proposition 3 *The price mark-up of the dominant oil producer is given by*

$$\mu = (Ta)\, r_k^{\hat{\gamma} - \tilde{\gamma}}, \tag{14}$$

where $r_k = g_z/\beta + \delta - 1$ is the rental rate of capital used in oil production and $Ta = \hat{Z}\hat{\gamma}^{\hat{\gamma}}(1 - \hat{\gamma})^{1-\hat{\gamma}} / \left(\tilde{Z}\tilde{\gamma}^{\tilde{\gamma}}(1-\tilde{\gamma})^{1-\tilde{\gamma}}\right)$ is the technological advantage of the dominant producer with respect to the fringe.

Proof. Since there are no barriers to entry in the competitive fringe, fringe producers must earn zero profits. Thus, the real price of oil must equal the marginal cost of the competitive fringe,

$$s = \widetilde{MC} = r_k^{1-\tilde{\gamma}} / \left[\tilde{Z}\tilde{\gamma}^{\tilde{\gamma}}(1-\tilde{\gamma})^{1-\tilde{\gamma}}\right], \tag{15}$$

The same formula replacing hats with tildes gives the marginal cost of the dominant producer,

$$\widehat{MC} = r_k^{1-\hat{\gamma}} / \left[\hat{Z}\hat{\gamma}^{\hat{\gamma}}(1-\hat{\gamma})^{1-\hat{\gamma}}\right]. \tag{16}$$

The oil price markup for the dominant firm is the ratio of price s to own marginal cost $\widehat{MC}$. ■

Corollary 4 *Consider the special case in which $\tilde{\gamma} = \hat{\gamma}$ (the two production technologies are symmetric). A dominant producer can exist profitably as long as it enjoys a permanent cost advantage, namely $\hat{Z} > \tilde{Z}$.*

Proof. In the symmetric case ($\tilde{\gamma} = \hat{\gamma}$), the oil price markup (14) reduces to $\mu = \hat{Z}/\tilde{Z}$. The dominant producer will thus be profitable if and only if $\hat{Z} > \tilde{Z}$. ■

Corollary 5 *The existence of a positive oil price markup implies a permanent GDP loss for oil importers.*

In our benchmark parameterization, the oil price markup of 20% translates into a permanent GDP loss of 0.7% with respect to the efficient (potential) level of GDP.

4.3 Capacity utilization

Writing the production function for oil as

$$O = Zu(X, K)K \tag{17}$$

we propose the following

Definition 6 *The capacity utilization rate of installed capital is given by* $u(X, K)$*, with* $u(0, K) = 0$*,* $\partial u/\partial X > 0$*, and* $\partial^2 u/\partial X^2 < 0$*. In the Cobb-Douglas case,* $u(X, K) = (X/K)^{\gamma}$ *.*

Using the above definition, we can derive an expression for the capacity utilization of the dominant oil producer *relative* to that of the competitive fringe,

$$u(\hat{X}, \hat{K})/u(\tilde{X}, \tilde{K}) = \left(\hat{X}/\hat{K}\right)^{\hat{\gamma}} / \left(\tilde{X}/\tilde{K}\right)^{\tilde{\gamma}} = (\hat{\gamma}\widehat{MC})^{\frac{\hat{\gamma}}{1-\hat{\gamma}}}/(\tilde{\gamma}\widetilde{MC})^{\frac{\tilde{\gamma}}{(1-\tilde{\gamma})}}, \tag{18}$$

where $\widetilde{MC}$ and $\widehat{MC}$ are defined in (15) and (16) respectively.

Given that in practice competitive producers operate virtually at full capacity, the above expression can be used to infer the capacity utilization rate of the dominant oil producer. For our calibrated parameter values, we obtain a value of 75%, which is consistent with the capacity utilization rate of Saudi Arabia documented in Section 2.

5 Oil Market Dynamics

5.1 Matching the historical volatilities

We set parameter χ to 2000 so that investment in oil production capacity peaks roughly two years after an oil price peak. We next calibrate the two shock processes as follows: we fix the two persistence parameters ρ_Z and $\rho_{\tilde{A}}$ to 0.944, equivalent to 0.5 on an annual basis. We then pick the standard deviations of the two innovations σ_Z (0.004) and $\sigma_{\tilde{A}}$ (0.04) so as to match the monthly volatility (standard deviations) of six series: Saudi Arabia's market share; the log-differences of total oil supply, Saudi Arabia's oil supply, and the oil supply of the rest of the oil producers; the log-difference of the real oil price; and of US industrial production. Table 3 shows the fit of our model to the relevant second moments.[8]

The model is quite successful at reproducing the historical volatility of the series of interest.[9] In particular, while it slightly underpredicts the volatility of total oil output, and somewhat overpredicts the volatility of total final goods output, it matches quite well the historical volatility of the real oil price, Saudi Arabia's oil production and fringe output. Key parameters for matching the two most volatile series (the real oil price and Saudi output) are the low elasticity of oil demand ($1/\eta = 0.05$) and the higher variable input share of the dominant firm ($\hat{\gamma} = 0.5$). In particular, the low elasticity of oil demand with respect to the oil price helps to explain the highly volatile oil price, while the higher variable input share of the dominant firm relative to the fringe enables us to explain the more volatile output of Saudi Arabia as the result of higher spare capacity.

5.2 Impulse-responses

Figure 2 shows the impulse-responses to a type of "negative oil supply shock", namely a 4% drop in the productivity of competitive fringe producers. As a result of this shock, fringe output falls by about 1.4%, while the output of the dominant producer increases by as much as 6%, raising its market share by around 0.8 percentage points. The increased production of Saudi Arabia is not enough to fully offset the output decline of the fringe and therefore total oil supply falls by around 0.4%, while the oil price rises by 8%. The latter produces a contraction of GDP in the oil importing region by around 0.3 percentage

[8] Data on oil supply (in million barrels per day) are taken from the Energy Information Administration's *Monthly Energy Review*. The real oil price is the nominal spot West Texas Intermediate price, deflated by U.S. CPI. Data on the nominal oil price, U.S. CPI, and U.S. industrial production are taken from the FRED II online database.

[9] We linearize and solve the model with the Dynare package.

points. These responses are in line with the observed reactions during the two oil supply shock episodes discussed in section 2.2 (the Iranian revolution and the first Gulf war). In both cases the fall in fringe production – of Iran in the first episode and Iraq and Kuwait in the second – was accompanied by a surge in the oil price and a sharp increase in Saudi Arabia's oil output (recall figure 1).

In figure 3 we show the impulse-responses to a type of "positive oil demand shock", namely an unexpected 0.4% rise in the *growth rate* of TFP of oil importers. As a result of this shock, the oil price rises gradually, peaking at 6% above its steady-state path around two years after the initial impulse. In this case both competitive fringe producers and the dominant oil supplier increase their output, although the dominant producer does so faster meaning that its market share increases slightly. These responses are consistent with the two episodes of (negative) oil demand shocks (the dotcom bust and the subprime crisis). In both cases Saudi Arabia reduced significantly oil output in response to falling global demand and oil prices.

In contrast to the previous shock, this time the oil price rise is associated with an increase in the GDP of oil importers tracking the cumulative rise in importers' TFP. As pointed out by Kilian (2009), Nakov and Pescatori (2010a,b), and Campolmi (2008), it is only natural that different fundamental shocks should produce different comovements between the oil price, oil supply, and GDP.

The above exercises build confidence that our simple model can explain some of the main patterns observed in the data. In particular, the model matches the historical volatilities of oil prices and quantities, and is able to capture the main comovements among the series. Profit maximization on behalf of the dominant producer with spare capacity goes a long way in explaining why Saudi Arabia increases strongly its output in response to supply disruptions elsewhere, while it reduces its production aggressively when oil importers are hit by a recession.

Finally, the model generates plausible investment dynamics in line with evidence documented by the International Energy Agency (2009). Namely, facing falling oil prices oil producers tend to cutback on investment, constraining future production possibilities and planting the seeds of future oil price rises. This pattern shows up in the case of a "negative oil demand shock" (the mirror image) in figure 3.

6 Scenario Analysis

An important advantage of DSGE models is the ability to analyze the impact of structural changes in a coherent way. In this section we explore three alternative hypothetical future scenarios: (1) perfect competition in oil production with access to the best available technology; (2) a permanent increase in the production costs of the competitive fringe (fringe oil "peaks"); (3) a symmetric permanent increase in oil production costs of the fringe and the dominant producer (oil peaks globally). Tables 4 and 5 report the level and volatility effects of these counterfactual simulations.

6.1 Perfect competition

This is a hypothetical scenario in which the oil fields of the dominant producer are opened to free competition. In this case all oil production would take place using the cheaper (Saudi) technology. Since access is free, there is no spare capacity and oil profits are competed away.

Results in table 4 show that, with respect to the baseline, the oil price is 20% lower, oil production is 1.1% higher and the GDP of oil importers is permanently higher by 0.7%. The oil expenditure share of GDP of oil importers is reduced to 4.6%.

Table 5 shows that in this scenario the oil price is slightly less volatile. In fact, if we assume that free access to Saudi oil production technology also implies lack of TFP shocks in oil production (as is currently assumed for the dominant firm), then, of course, the oil price would be much less volatile (down to 1.1%), and the volatility of oil output and GDP will also be reduced.

6.2 Fringe production costs increase

In this scenario we assume that the productivity of the competitive fringe is lowered by half ($\tilde{Z} = 0.5$), while everything else remains the same. This case is intended to reflect the fact that competitive producers are relatively low on oil reserves and new discoveries in the fringe are likely to involve more costly technologies.

In table 4 we show that the reduction in the productivity of the fringe by half doubles its marginal costs and hence it doubles the oil price. The higher oil price results in a 3.5% reduction in oil demand and a similar permanent reduction of the GDP of oil importers. Because of the higher cost of oil, importers now devote about 11.5% of GDP to meet their oil bill, compared with 5.7% in the baseline scenario. The change affects also the market shares: in the new steady-state the dominant producer supplies almost a third of the world's oil and charges a markup of 60%, three times larger than the markup achieved in the baseline scenario. While the dominant producer maintains its baseline capacity utilization rate of 75%, in absolute terms its spare capacity is now equivalent to 10% of world production (compared to 4% in the baseline).

In table 5 we report a significant reduction in the volatility of Saudi oil production. This is explained by the reduction in the market share of fringe producers, so that shocks to the fringe of the same size as before now affect oil market conditions much less than before.

6.3 Global production costs increase

Finally, we assume that both types of oil producers experience a permanent doubling of costs ($\hat{Z}$ falls from 2 to 1, while $\tilde{Z}$ falls from 1 to 0.5).

In table 4, since the oil price equals marginal cost for competitive producers, the oil price doubles as before. Both oil output and GDP are 3.5% lower than baseline as in the previous scenario, and the oil share in GDP rises to 11.5%. The difference with respect to the previous scenario is that in this case the oil markup of the dominant producer is maintained at its baseline level since the ratio of oil productivities of the two types of producers is unchanged. In table 5, we find no significative difference in terms of the volatilities of the series between this scenario and the baseline.

7 Oil Taxes in General Equilibrium

As we have seen in section 4.2, the presence of a dominant oil producer introduces a distortion in the oil production process. A natural question is whether oil importing countries could mitigate or perhaps even eliminate this distortion with suitable a fiscal policy. One possibility often discussed in the media is the introduction of a proportional tax on oil consumption. Another option is a production subsidy to oil producers.[10] In this section we study such possibilities as well as the robustness of the results to decreasing returns to scale in oil production.

7.1 Oil consumption tax / import duty

Here we study the effects of a proportional tax on oil consumption rebated to the oil-importing consumer in a lump-sum manner. This requires us to modify the budget constraint of the oil importing households as follows

$$C_t + (1+\tau)\, s_t O_t = w_t L_t + T_t, \tag{19}$$

where $(1+\tau)\, s_t$ is the effective price of oil paid by the consumer and $T_t = \tau s_t O_t$ is a lump-sum rebate. Naturally, the tax affects the optimal oil / final goods consumption mix of the oil importer

$$\nu_t C_t = (1+\tau)\, s_t O_t^{\eta}, \tag{20}$$

which is "understood" by the dominant oil producer (reflected in the fact that τ now appears in its first order profit-maximization conditions).

In general, it is not clear *a priori* how the burden of the tax is shared between the oil consumer and the oil producers. At least in principle, it is possible that a higher oil consumption tax, by discouraging oil consumption, reduces the price of oil so that some of the tax is effectively paid by oil producers.

[10] E.g. "Raise the Gas Tax" by Gregory Mankiw. *The Wall Street Journal*, October 20, 2006; The Pigou Club Manifesto, http://gregmankiw.blogspot.com/2006/10/pigou-club-manifesto.html

Figure 4, panel (3,1), shows that, indeed, oil consumption is discouraged by a positive oil consumption tax ($\tau > 0$). Resources previously used up in oil consumption are now freed and redirected to final goods consumption (1,1) and to more leisure (2,1). However, the fact that GDP increases while labor hours are reduced does not necessarily imply that welfare rises. Indeed, panel (4,2) of the figure shows that the utility gain from increased goods consumption (1,2) and leisure (2,2) is more than offset by the loss of utility from less oil consumption (3,2). At the same time, an oil consumption subsidy ($\tau < 0$), while increasing oil consumption and the utility derived thereof, reduces final goods consumption and leisure in a way that total utility again is reduced. Thus, in our baseline model with constant returns to scale in oil production, the optimal oil consumption tax is zero from a welfare point of view, despite the fact that final goods consumption increases while hours worked fall with a positive tax.

7.2 Oil production subsidy

We now turn to the case of an oil production subsidy. The latter may work by offsetting what is effectively an oil production tax: the presence of a dominant oil producer supplying less oil than the competitive level of output at a higher price. The way we implement the subsidy is as a subsidy to the investment good purchased by the competitive fringe to build up oil production capacity. This implies that the household's budget constraint of the competitive fringe is now

$$\tilde{C}_t + (1+\phi)\tilde{I}_t = \tilde{r}_t^k \tilde{K}_{t-1} + \tilde{D}_t$$

with $\phi < 0$ denoting the investment subsidy (and $\phi > 0$ denoting a tax). We assume that the resources needed for the subsidy are raised in a lump-sum manner from the oil importing country,

$$C_t + s_t O_t = Y_t + T_t$$

with $T_t = \phi \tilde{I}_t$.

Figure 5, panel (4,2) shows that a relatively modest production subsidy to the fringe would indeed raise welfare of oil importers. In particular, the maximum welfare is achieved for an oil production subsidy of about 17% of the price of investment ($\phi = -0.17$), equivalent to 0.5% of the GDP of oil importers. The way the subsidy works is by making production of oil by the competitive fringe less costly, increasing oil supply, and lowering the oil price markup and market share of the dominant oil producer. Up to the optimal level of the subsidy, the additional utility due to increased oil consumption more than compensates the loss of utility from consuming less final goods and working more hours. Beyond that level, however, the added utility of oil consumption is outweighed by the disutility from consuming less final goods and working more hours.

7.3 Oil consumption tax with decreasing returns in oil production

In sections 7.1 and 7.2 we found that the welfare of the oil importer is maximized with a zero oil consumption tax but a positive oil production subsidy. These results can be traced back to the assumption of constant returns to scale in oil production. As equation (15) shows, constant returns to scale imply that the oil price is determined by technological parameters and the rental rate of capital (which itself is pinned down by the households' time preference and capital depreciation rate). A production subsidy works because it effectively lowers the rental rate of capital; a consumption tax does not work since it has no general equilibrium effect on the oil price and hence introduces an additional distortion without mitigating the one already in place.

Here we show that the latter result is overturned if oil is produced under decreasing returns to scale (as would be the case with a fixed factor of production). To simulate this scenario, we assume that capital does not accumulate endogenously, so that the oil production function, both of the dominant firm and of the competitive fringe, becomes

$$O_t = Z_t X_t^\gamma,$$

where $\gamma < 1$ and Z_t grows so as to ensure the balanced growth path property.

With this change we revisit the analysis of the oil consumption tax of section 7.1. Figure 6, panel (2,4), shows that welfare of the oil importer is maximized when the oil consumption tax is as high as

115% ($\tau = 1.15$). As before, a positive oil consumption tax reduces oil consumption and induces a shift towards more final goods consumption and leisure. Differently from the case with constant returns to scale, however, this time much of the tax ends up being paid by the dominant oil producer. In particular, oil profits sink due the general equilibrium effects of reduced oil demand lowering the oil price (and the oil price markup) charged by the dominant oil producer.

8 Conclusions

We document several facts about the oil market (the size distribution of oil firms, spare capacity, oil output and oil price comovements) which are hard to explain with a competitive framework in mind. We show nonetheless that the facts can be accounted for quantitatively by a fairly standard model of a dominant firm with competitive fringe. We use the model to simulate alternative future oil market scenarios and answer several questions on which existing models are silent. In particular, we quantify the distortion from the presence of the dominant oil producer in terms of the loss of output and utility for oil-importing countries. We also study the effects of proportional taxes on oil consumption or oil production subsidies. We find that, while an oil production subsidy to the competitive fringe in principle should work, an oil consumption tax may or may not bring welfare improvement depending on the degree of returns to scale in oil production. We expect future research to study these issues in greater detail.

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Appendix A:

Equilibrium conditions given any dominant producer's strategy

Here we summarize the (additional) conditions which constrain the decision problem of the dominant oil producer arising from the optimal behavior of the oil-importing region's households and firms and of the competitive fringe, as well as the resource constraints. These are the conditions that, together with the production functions for oil and final goods output, and the capital accumulation equations, the dominant firm needs to satisfy along its optimally chosen state-contingent oil supply plan.

Utility maximization by oil-importing households implies the following oil demand curve,

$$\nu_t C_t = s_t O_t^{\eta}, \tag{21}$$

and labor supply curve,

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

Profit maximization by final goods firms implies the following aggregate demand for labor,

$$w_t L_t = \alpha Y_t. \tag{23}$$

The optimal supply decision of fringe producers implies,

$$\tilde{\gamma} s_t = \tilde{X}_t / \tilde{O}_t. \tag{24}$$

Defining "Tobin's q" as the marginal value of installed capital, optimal capital accumulation by fringe producers implies

$$\tilde{q}_t = \beta E_t \left[\frac{\tilde{C}_t}{\tilde{C}_{t+1}} \left((1-\tilde{\gamma})\, s_{t+1} \frac{\tilde{O}_{t+1}}{\tilde{K}_t} + (1-\delta)\tilde{q}_{t+1} \right) \right], \quad \text{and} \tag{25}$$

$$1 = \tilde{q}_t \left[1 - \chi \left(\frac{\tilde{I}_t}{\tilde{I}_{t-1}} - G^z \right) \frac{\tilde{I}_t}{\tilde{I}_{t-1}} - \frac{\chi}{2} \left(\frac{\tilde{I}_t}{\tilde{I}_{t-1}} - G^z \right)^2 \right] + \beta \chi E_t \left[\frac{\tilde{q}_{t+1}\tilde{C}_t}{\tilde{C}_{t+1}} \left(\frac{\tilde{I}_{t+1}}{\tilde{I}_t} - G^z \right) \left(\frac{\tilde{I}_{t+1}}{\tilde{I}_t} \right)^2 \right] \tag{26}$$

Aggregate oil output O_t is the sum of dominant and fringe supply,

$$O_t = \hat{O}_t + \tilde{O}_t \tag{27}$$

Barring borrowing across regions, final good consumption of the oil-importing region equals output net of the value of oil imports,

$$C_t = Y_t - s_t O_t. \tag{28}$$

Finally, the global resource constraint,

$$Y_t = C_t + \tilde{C}_t + \hat{C}_t + \tilde{I}_t + \hat{I}_t + \tilde{X}_t + \hat{X}_t, \tag{29}$$

states that global output is the sum of global final goods consumption, global investment, and global intermediate good purchases.

Appendix B: Complete set of equations (not intended for publication)

Oil-importing region conditions

$$\nu_t C_t = s_t O_t^{\eta} \tag{30}$$

$$C_t L_t^{\psi} = w_t \tag{31}$$

$$Y_t = Z_t L_t^{\alpha} \tag{32}$$

$$w_t L_t = \alpha Y_t \tag{33}$$

Dominant oil producer conditions

$$\hat{C}_t = s_t \hat{O}_t - \hat{I}_t - \hat{X}_t \tag{34}$$

$$\hat{O}_t = \hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}} \tag{35}$$

$$\hat{X}_t = \hat{\gamma}\left(s_t + \lambda_{3t}\right)\hat{O}_t \tag{36}$$

$$\hat{K}_t = (1-\delta)\,\hat{K}_{t-1} + \left[1 - \frac{\chi}{2}\left(\frac{\hat{I}_t}{\hat{I}_{t-1}} - G^z\right)^2\right]\hat{I}_t, \tag{37}$$

$$\hat{q}_t = \beta E_t\left[\frac{\hat{C}_t}{\hat{C}_{t+1}}\left((1-\hat{\gamma})\,\frac{(s_{t+1}+\lambda_{3t+1})\hat{O}_{t+1}}{\hat{K}_t} + (1-\delta)\hat{q}_{t+1}\right)\right] \tag{38}$$

$$1 = \hat{q}_t\left[1 - \chi\left(\frac{\hat{I}_t}{\hat{I}_{t-1}} - G^z\right)\frac{\hat{I}_t}{\hat{I}_{t-1}} - \frac{\chi}{2}\left(\frac{\hat{I}_t}{\hat{I}_{t-1}} - G^z\right)^2\right] + \beta\chi E_t\left[\frac{\hat{q}_{t+1}\hat{C}_t}{\hat{C}_{t+1}}\left(\frac{\hat{I}_{t+1}}{\hat{I}_t} - G^z\right)\left(\frac{\hat{I}_{t+1}}{\hat{I}_t}\right)^2\right] \tag{39}$$

$$\lambda_{3t} = \lambda_{2t} s_t\left(1-\tilde{\gamma}\right) \tag{40}$$

$$\hat{O}_t = \lambda_{1t} O_t^{\eta} - \lambda_{2t}\tilde{\gamma}\tilde{O}_t + \lambda_{4t}\left(O_t^{\eta} + \nu_t O_t\right) \tag{41}$$

$$0 = \eta s_t O_t^{\eta-1}(\lambda_{1t} + \lambda_{4t}) + \lambda_{3t} + \lambda_{4t}\nu_t s_t \tag{42}$$

$$0 = \lambda_{1t}(\alpha - 1 - \psi) s_t O_t^{\eta} + \alpha\lambda_{4t}\nu_t Z_t L_t^{\alpha} \tag{43}$$

Competitive fringe producers' conditions

$$\tilde{C}_t = s_t \tilde{O}_t - \tilde{I}_t - \tilde{X}_t \tag{44}$$

$$\tilde{O}_t = \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}} \tag{45}$$

$$\tilde{X}_t = \tilde{\gamma} s_t \tilde{O}_t \tag{46}$$

$$\tilde{K}_t = (1-\delta)\,\tilde{K}_{t-1} + \left[1 - \frac{\chi}{2}\left(\frac{\tilde{I}_t}{\tilde{I}_{t-1}} - G^z\right)^2\right]\tilde{I}_t \tag{47}$$

$$\tilde{q}_t = \beta E_t\left[\frac{\tilde{C}_t}{\tilde{C}_{t+1}}\left((1-\tilde{\gamma})\,\frac{s_{t+1}\tilde{O}_{t+1}}{\tilde{K}_t} + (1-\delta)\tilde{q}_{t+1}\right)\right] \tag{48}$$

$$1 = \tilde{q}_t\left[1 - \chi\left(\frac{\tilde{I}_t}{\tilde{I}_{t-1}} - G^z\right)\frac{\tilde{I}_t}{\tilde{I}_{t-1}} - \frac{\chi}{2}\left(\frac{\tilde{I}_t}{\tilde{I}_{t-1}} - G^z\right)^2\right] + \beta\chi E_t\left[\frac{\tilde{q}_{t+1}\tilde{C}_t}{\tilde{C}_{t+1}}\left(\frac{\tilde{I}_{t+1}}{\tilde{I}_t} - G^z\right)\left(\frac{\tilde{I}_{t+1}}{\tilde{I}_t}\right)^2\right] \tag{49}$$

Market clearing conditions

$$O_t = \hat{O}_t + \tilde{O}_t \tag{50}$$

$$C_t = Y_t - s_t O_t \tag{51}$$

Appendix C: Tables and figures

Table 1. Production and capacity of major oil producers

	Production share Mean (%)	Production growth Mean (YoY %)	Std. (YoY %)	Spare capacity (% world supply)
OPEC	40.7	0.1	45	7.8
Iran	5.8	-1.1	153	0.3
Iraq	2.9	1.2	563	0.1
Kuwait	2.9	-1.3	403	0.5
Saudi Arabia	12.3	0.4	83	3.9
UAE	3.2	1.5	74	0.7
Venezuela	3.9	-1.2	102	0.3
Non OPEC	59.3	1.4	10	-
China	4.3	3.6	36	-
Mexico	3.9	4.9	53	-
Russia	15.3	0.4	16	-
USA	12.0	-1.6	27	-
World	100.0	0.8	20	-

All statistics are based on monthly data from 1.1973 to 4.2009. Source: EIA (2009) and IEA (2009)

Table 2. Data and model-implied averages

%	Saudi share	Oil output growth	Oil price growth	Oil/GDP	Final output growth
Data	12.3	0.78	2.21	5.0	2.98
Model	12.7	0.77	2.21	5.7	3.00

Table 3. Data and model-implied standard deviations

	Oil price	Oil output	Fringe output	Saudi output	Saudi share	Final output
Data	8.5	1.7	1.5	6.9	2.6	0.7
Model	8.3	1.2	1.8	6.4	2.7	1.2

Except "Saudi share" all numbers are standard deviations (in percentage points) of first log differences.

Table 4. Comparative statics: changes from the baseline scenario

	Levels				Changes from baseline (%)		
	Markup	SA share	Oil/GDP	Cap. Util.	GDP	Oil price	Oil output
Baseline	20%	12.7%	5.7%	75%	-	-	-
Higher fringe costs	60%	30.8%	11.5%	75%	-3.5%	100%	-3.5%
Higher global costs	20%	12.7%	11.5%	75%	-3.5%	100%	-3.5%
Competitive market	0%	0%	4.6%	100%	0.7%	-20%	1.1%

Note: the last three columns are percentage changes from the steady state in the baseline scenario.

Table 5. Standard deviations under the different scenarios

	Oil price	Oil output	Fringe output	Saudi output	Saudi share	GDP
Baseline	8.3	1.2	1.8	6.4	2.7	1.2
Higher fringe costs	7.9	1.2	1.9	2.6	2.5	1.2
Higher global costs	8.2	1.2	1.8	6.4	2.7	1.2
Competitive market	7.8	1.2	1.2	1.2	-	1.2

Note: except "Saudi share" all numbers are standard deviations (in percentage points) of first log differences.

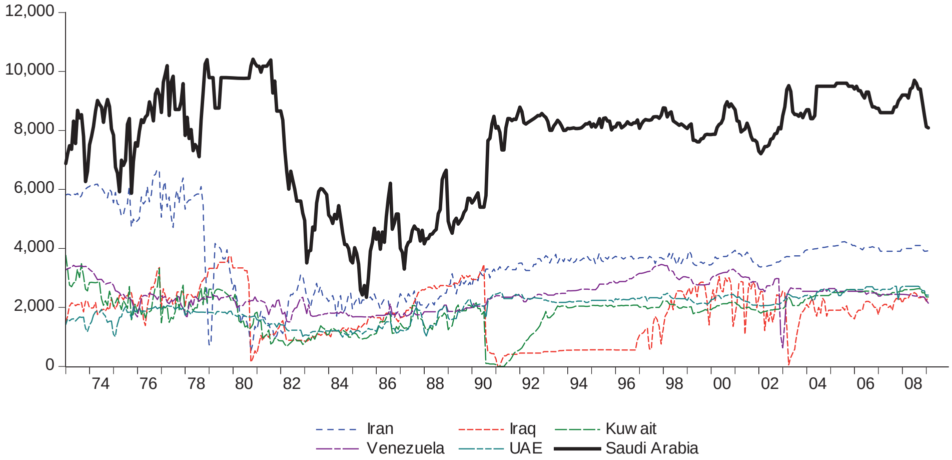

Figure 1: Oil supply by six large OPEC producers, 1973-2009

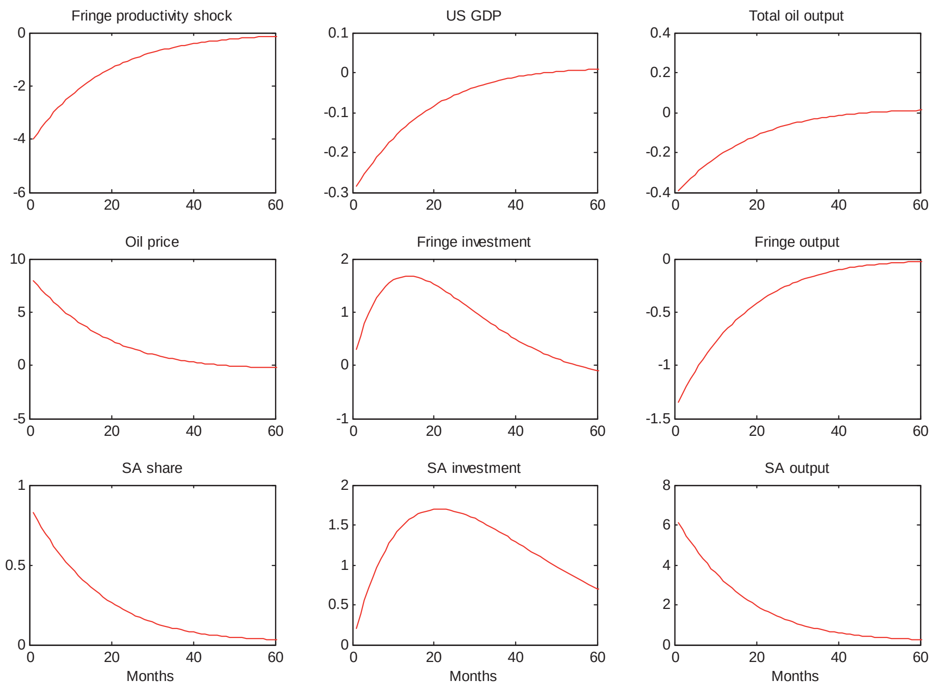

Figure 2: Oil supply shock: 4% drop in competitive fringe productivity

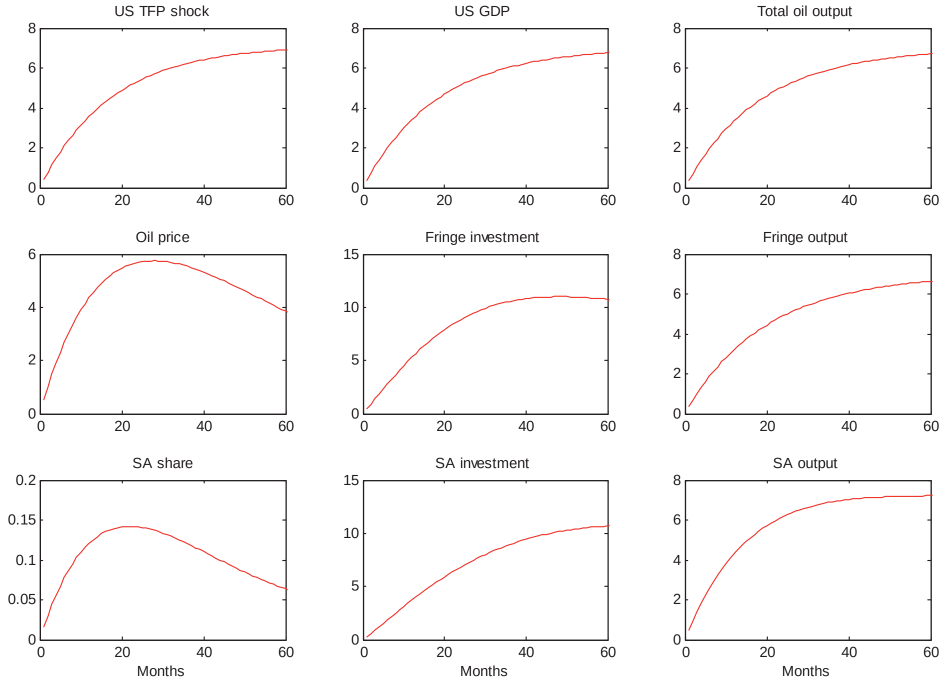

Figure 3: Oil demand shock: 0.4% increase in the growth rate of importer's TFP

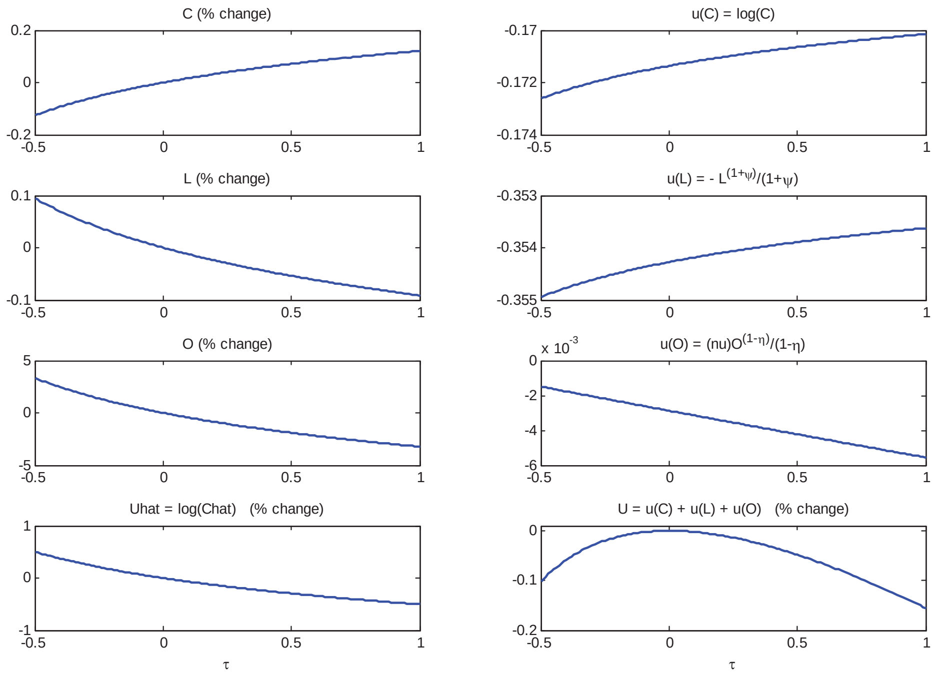

Figure 4: Effects of an oil consumption tax

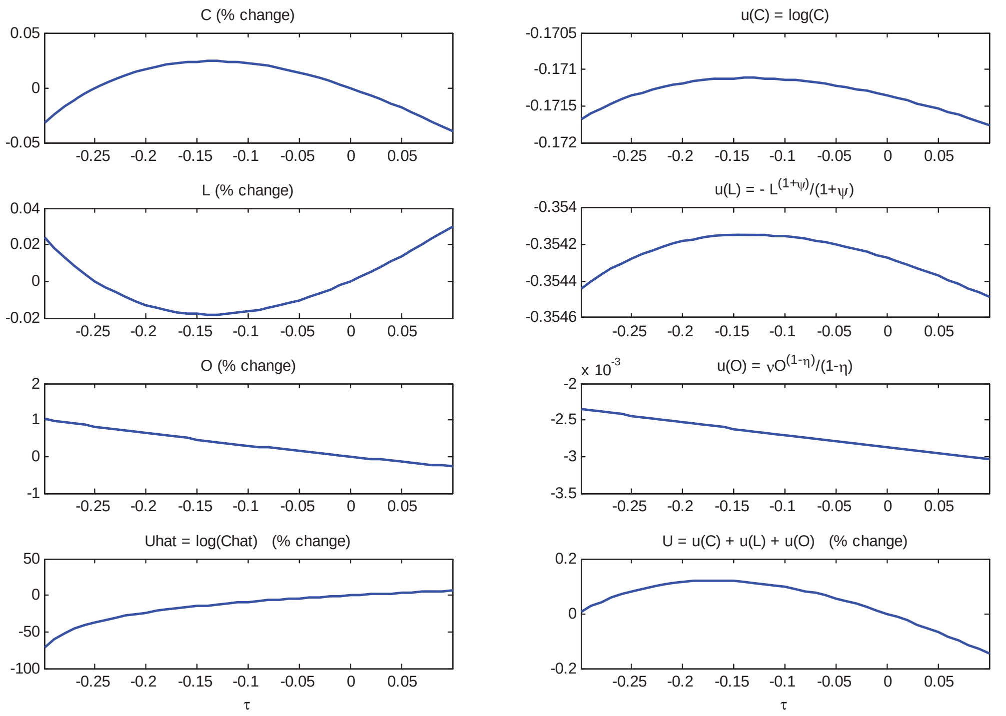

Figure 5: Effects of an oil production tax

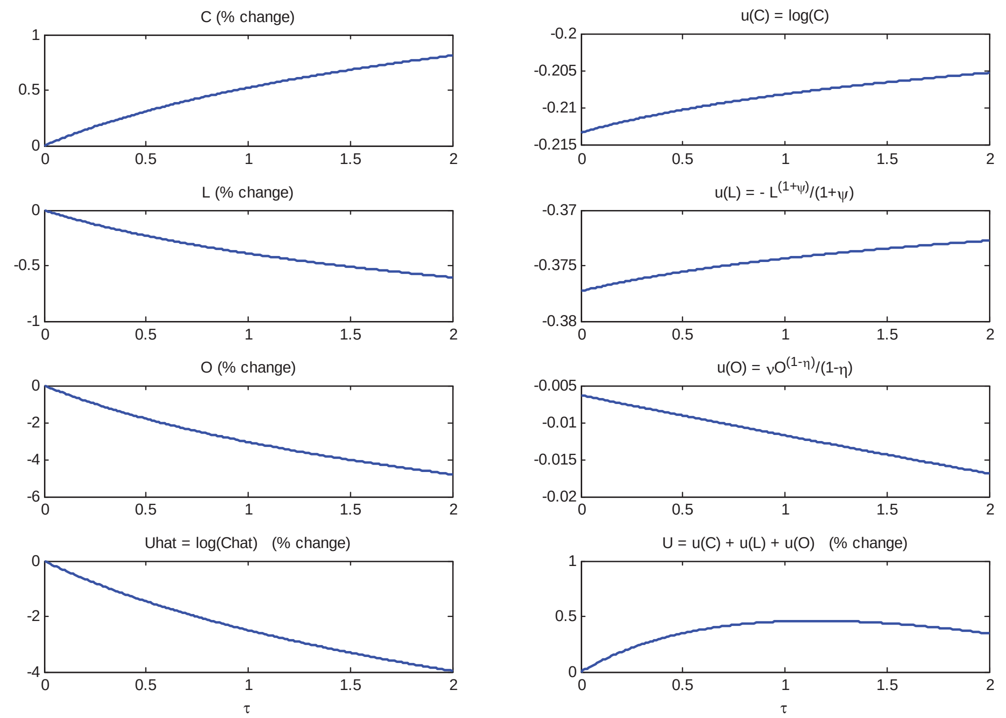

Figure 6: Oil consumption tax with decreasing returns to scale

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Alcalá, 522; 28027 Madrid
Teléfono +34 91 338 6363. Fax +34 91 338 6488
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