Oilgopoly: a general equilibrium model of the oil-macroeconomy nexus

Anton Nakov and Galo Nuño

Banco de España

May 2010
Where is the oil?

Saudi Arabia is the world’s largest oil producer
Where is the oil?

Saudi Arabia owns the largest known oil fields

PROVED RESERVES 2002*

- Middle East 65.4%
- Saudi Arabia 25%
- Africa 7.4%
- North America 4.8%
- Asia Pacific 3.7%
- Europe and Eurasia 9.3%
- Central and South America 9.4%

*Proved reserves are those that the industry considers can be recovered in existing economic and operating conditions.

SOURCE: BP
Other oil producers are smaller

Top ten oil companies, ranked by production, 2007

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>State-owned (%)</th>
<th>Output (mbpd)</th>
<th>Reserves (bil. barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aramco</td>
<td>Saudi Arabia</td>
<td>100</td>
<td>10.4</td>
<td>264.2</td>
</tr>
<tr>
<td>NIOC</td>
<td>Iran</td>
<td>100</td>
<td>4.4</td>
<td>138.4</td>
</tr>
<tr>
<td>Pemex</td>
<td>Mexico</td>
<td>100</td>
<td>3.5</td>
<td>12.2</td>
</tr>
<tr>
<td>CNPC</td>
<td>China</td>
<td>100</td>
<td>2.8</td>
<td>22.4</td>
</tr>
<tr>
<td>Exxon Mobil</td>
<td>US</td>
<td></td>
<td>2.6</td>
<td>11.1</td>
</tr>
<tr>
<td>KPC</td>
<td>Kuwait</td>
<td>100</td>
<td>2.6</td>
<td>101.5</td>
</tr>
<tr>
<td>PDV</td>
<td>Venezuela</td>
<td>100</td>
<td>2.6</td>
<td>99.4</td>
</tr>
<tr>
<td>BP</td>
<td>UK</td>
<td></td>
<td>2.4</td>
<td>10.1</td>
</tr>
<tr>
<td>INOC</td>
<td>Iraq</td>
<td>100</td>
<td>2.1</td>
<td>115.0</td>
</tr>
<tr>
<td>Rosneft</td>
<td>Russia</td>
<td>75</td>
<td>2.0</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Source: Smith (2009) and Petroleum Intelligence Weekly, December 4, 2008
Saudi Aramco as a dominant firm

“OPEC is Saudi Arabia”
– Mabro (1975)

“The Saudis have acted as what they are: the leading firm in the world oil market”
– Adelman (1995)
Saudi Arabia’s oil output has been highly volatile ...  
Output of the largest OPEC producers (tbd)
... even if the Kingdom has been an “island of stability”

Instances when Saudi production was directly affected by exogenous events

- 1977 fire at the Abqaiq facilities
- 1984 several Saudi tankers destroyed during the Iran-Iraq war
- 1991 attacks by Iraqi missiles during the Gulf war

“Official Oil Market Chronology”
- U.S. Energy Information Administration

Apart from these episodes, changes in Saudi oil output were the result of production decisions; not the consequence of disruptions in its production capabilities.
Underinvestment and shutting-in existing capacity

- Saudi Arabia is the only producer which “shuts in” significant spare capacity
  - It could add 4% to world oil supply in 2009 just by tapping existing wells (IEA) (equivalent to the entire production of Kuwait, Venezuela, or Norway)
- It restricts the growth of new capacity (Smith, 2009)
Historical episodes

- **Iranian revolution**: Iran’s production collapsed from 6 mbd in 9/1978 to 0.7 mbd in 1/1979. Saudi Arabia raised its output from 8.3 mbd to 10.4 mbd (25% in 3 months)

- **The Gulf war**: Iraqi + Kuwaiti output collapsed from 5.3 mbd in 7/1990 to zero in 2/1991. Saudi Arabia’s output jumped from 5.4 mbd to 8.4 mbd (56% in 5 months)

- **2001 recession**: From 1/2001 to 12/2001 OPEC cut supply by 2.5 mbd; of this, 1.1 mbd was due to Saudi Arabia

- **Subprime crisis**: Between 7/2008 and 1/2009, world oil supply fell by 3.2 mbd; 1.6 mbd was due to Saudi Arabia.
Questions

- How can one rationalize the behavior of Saudi Arabia?
  - Stagnant investment in new capacity
  - Low utilization rate of installed capacity
  - Highly volatile output despite internal stability
  - Offsetting output collapses of other producers

- What impact does it have on the oil market as a whole?

- What are the (GE) effects of a tax on oil consumption / production?
Our take

- A competitive model cannot account for these facts
- Instead, we model Saudi Arabia as a dominant firm, with the rest of oil producers as a competitive fringe
- The behavior of the dominant firm can be seen as a profit maximizing response
  - Underinvestment in new capacity raises the average oil price
  - Spare capacity allows fast adjustment of output as necessary in response to demand and supply shocks
- Bonus:
  - A quantitative DSGE model with endogenous oil price and oil supply decisions
  - Can study the effects of different oil shocks ("not all oil shocks are alike")
  - Derive long run implications and perform comparative statics
  - Study the effects of oil taxes in general equilibrium
Related literature

- Transmission of exogenous oil price shocks
  Kim and Loungani (1992), Leduc and Sill (2004), ...

- Overwhelming evidence against exogenous oil prices
  Barsky and Kilian (2004); Kilian (2008)

- Despite this evidence, few general equilibrium models treat the oil price as endogenous
  Leduc and Sill (2007), Bodenstein et. al. (2008), Campolmi (2008)

- Even fewer determine endogenously the oil price *and* quantity
  Backus and Crucini (2000)

- We model oil supply as a dominant firm with comp. fringe
  Nakov and Pescatori (*JMCB*, 2010)
Model

- Three regions: one oil-importing and two oil-exporting ones
- The oil-importer uses oil in consumption, and uses labor to produce final goods, part of which are consumed domestically, with the rest exported to the oil-producers
- Oil is a homogeneous commodity supplied by two types of producers: a dominant firm and a “competitive fringe”
- The fringe takes the oil price as given
- The dominant producer faces a downward sloping “residual demand” curve, picking profit-maximizing points
- Oil exporters produce oil only, and their revenues are recirculated to the oil importer as demand for final goods
- We allow no borrowing across regions and abstract from monetary and exchange rate factors
A representative household maximizes utility

\[
\max_{C_t, O_t, L_t, B_t} E_o \sum_{t=0}^{\infty} \beta^t \left[ \log(C_t) + \nu_t \frac{O_t^{1-\eta}}{1-\eta} - \frac{L_t^{1+\psi}}{1+\psi} \right]
\]

subject to the budget constraint

\[
C_t + s_t O_t + B_t = w_t L_t + (1 + r_{t-1}) B_{t-1} + D_t
\]

A representative firm produces final goods under perfect competition

\[
Y_t = Z_t L_t^\alpha
\]

where \( \Delta \log(Z_t) = \rho_z \Delta \log(Z_{t-1}) + \varepsilon^z_t \).

The firm chooses its labor input to maximize profits.
Model

Fringe producers

A representative household maximizes

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

$$\text{s.t.: } \tilde{C}_t + \tilde{I}_t = \tilde{r}_t^k \tilde{K}_{t-1} + \tilde{\Pi}_t$$

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

A representative competitive firm maximizes period profits $\tilde{\Pi}_t$,

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

taking the oil price as given, and subject to $\tilde{O}_t = \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}}$, where $\tilde{Z}_t = \tilde{A}_t \tilde{Z} \exp(g^z t)$, with $\tilde{Z} \exp(g^z t)$ a deterministic trend, and $\tilde{A}_t$ a stationary AR(1) process.
Model
Dominant oil producer

The dominant oil producer maximizes the household’s utility of consumption

$$\max E_o \sum_{t=0}^{\infty} \beta^t \log (s_t \hat{Z}_t \hat{X}_t \hat{K}_{t-1}^{1-\hat{\gamma}} - \hat{I}_t - \hat{X}_t).$$

(8)

Oil is produced according to

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

(9)

where technology evolves deterministically \( \hat{Z}_t = \hat{Z} \exp(g^2 t) \).

The firm accumulates capital according to

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

(10)
Model

Dominant oil producer decision problem

$$\max_{\hat{C}_t, \hat{K}_t, \hat{I}_t, \hat{X}_t, \hat{x}_t, s_t, O_t, L_t} E_o \sum_{t=0}^\infty \beta^t \log (s_t \hat{Z}_t \hat{X}_t \hat{K}_t^{1-\gamma} - \hat{I}_t - \hat{X}_t)$$  \hspace{1cm} (11)

subject to

$$s_t O_t^\gamma = \nu_t \alpha Z_t L_t^{\alpha-1-\psi}$$  \hspace{1cm} (12)

$$\tilde{X}_t = \tilde{\gamma} s_t \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}}$$  \hspace{1cm} (13)

$$O_t = \hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}} + \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}}$$  \hspace{1cm} (14)

$$s_t O_t^\gamma = \nu_t Z_t L_t^{\alpha} - \nu_t s_t O_t$$  \hspace{1cm} (15)

$$\hat{K}_t = (1 - \delta) \hat{K}_{t-1} + \left[ 1 - \chi \left( \hat{I}_t / \hat{I}_{t-1} - G^z \right)^2 \right] \hat{I}_t$$  \hspace{1cm} (16)
Calibration

Steady state

Table 3. Data and model-implied averages

<table>
<thead>
<tr>
<th>%</th>
<th>Saudi share</th>
<th>Oil output growth</th>
<th>Oil price growth</th>
<th>Oil/GDP</th>
<th>Final output growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>12.3</td>
<td>0.78</td>
<td>2.21</td>
<td>5.0</td>
<td>2.98</td>
</tr>
<tr>
<td>Model</td>
<td>12.7</td>
<td>0.77</td>
<td>2.21</td>
<td>5.7</td>
<td>3.00</td>
</tr>
</tbody>
</table>
Secular Features of the Oil Market

Conditions for balanced growth

Lemma
The real price of oil grows at rate $-g^\ddot{z}$. 

Proof.
Since $O_t$ grows at rate $g^z + g^\ddot{z}$, 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 $-g^\ddot{z}$. □

Lemma
Oil efficiency $\nu_t$ grows at rate $(\eta - 1) \left( g^z + g^\ddot{z} \right)$. 

Proof.
Along the balanced growth path $C_t$ grows at rate $g^z$ while $s_t O_t^\eta$ grows at rate $\eta \left( g^z + g^\ddot{z} \right) - g^\ddot{z}$. Hence, along the balanced growth path $\nu_t$ must grow at rate $(\eta - 1) \left( g^z + g^\ddot{z} \right)$. □
Secular Features of the Oil Market

Oil price markup

Lemma

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

\[
\mu = \frac{\hat{Z} \hat{Y} (1 - \hat{\gamma})^{1 - \hat{\gamma}}}{\tilde{Z} \tilde{Y} (1 - \tilde{\gamma})^{1 - \tilde{\gamma}} r_k^{\hat{\gamma} - \tilde{\gamma}},}
\]

(17)

where \( r_k = g_z / \beta + \delta - 1 \) is the rental rate of capital in oil production.

Proof.

No barriers to entry in the competitive fringe \( \Rightarrow \) fringe producers make zero profits. The real price of oil equals the marginal cost of the fringe

\[
s = \bar{MC} = \frac{r_k^{1 - \tilde{\gamma}}}{\tilde{Z} \tilde{Y} (1 - \tilde{\gamma})^{1 - \tilde{\gamma}}}. \]

(18)
Proof. [Proof (cont’d)] A similar formula gives the marginal cost of the dominant producer,

$$\widehat{MC} = \frac{r_k^{1 - \hat{\gamma}}}{\hat{Z}^{\hat{\gamma}}(1 - \hat{\gamma})^{1 - \hat{\gamma}}}.$$  \hfill (19)

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

Corollary

Special case $\tilde{\gamma} = \hat{\gamma}$ (symmetric technologies). A dominant producer persists as long as it has a cost advantage, $\hat{Z} > \tilde{Z}$. 

Can write the production function for oil as $O = Zu(X, K)K$

**Definition**
The capacity utilization rate of installed capital is defined as $u(X, K)$, with $u(0, K) = 0$, $\partial u/\partial X > 0$, and $\partial^2 u/\partial X^2 < 0$.

In the Cobb-Douglas case, $u(X, K) = (X/K)^\gamma$.

Capacity utilization of the dominant oil producer relative to that of the competitive fringe

$$\frac{u(\hat{X}, \hat{K})}{u(\tilde{X}, \tilde{K})} = \left(\frac{\hat{X}}{\hat{K}}\right)^\hat{\gamma} = \frac{\left(\hat{\gammaMC}\right)^{\hat{\gamma}}}{\left(\tilde{\gammaMC}\right)^{1-\hat{\gamma}}}.$$  \hspace{1cm} (20)
Oil Market Dynamics
Matching the historical volatilities

<table>
<thead>
<tr>
<th>Shock and elasticity parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_Z$</td>
</tr>
<tr>
<td>0.944</td>
</tr>
</tbody>
</table>

Table 4. Data and model-implied standard deviations

<table>
<thead>
<tr>
<th></th>
<th>Oil price</th>
<th>Oil output</th>
<th>Fringe output</th>
<th>Saudi output</th>
<th>Saudi share</th>
<th>Final output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>8.5</td>
<td>1.7</td>
<td>1.5</td>
<td>6.9</td>
<td>2.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Model</td>
<td>8.3</td>
<td>1.2</td>
<td>1.8</td>
<td>6.4</td>
<td>2.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Standard deviations (in pp) of first log differences (except “Saudi share”)
Oil Market Dynamics: Impulse-responses

Oil "supply" shock: 4% drop in competitive fringe productivity
Oil Market Dynamics: Impulse-responses

Oil "demand" shock: 0.4% increase in the growth rate of importer’s TFP
Scenario Analysis

- Competitive oil market
- Fringe oil peaks
- All oil peaks

Table 5. Comparative statics

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mark-up</th>
<th>SA share</th>
<th>Oil/GDP</th>
<th>Cap. Util.</th>
<th>GDP %Δ</th>
<th>Oil output %Δ</th>
<th>Oil price %Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>20</td>
<td>12.7</td>
<td>5.7</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compet.</td>
<td>0</td>
<td>0</td>
<td>4.6</td>
<td>100</td>
<td>+0.7</td>
<td>+1.1</td>
<td>−20</td>
</tr>
<tr>
<td>Fr. costs ↑</td>
<td>60</td>
<td>30.8</td>
<td>11.5</td>
<td>75</td>
<td>−3.5</td>
<td>−3.5</td>
<td>+100</td>
</tr>
<tr>
<td>Oil costs ↑</td>
<td>20</td>
<td>12.7</td>
<td>11.5</td>
<td>75</td>
<td>−3.5</td>
<td>−3.5</td>
<td>+100</td>
</tr>
</tbody>
</table>

Note: last three columns are % changes from the baseline steady state
Tax Analysis

Proportional tax on oil consumption rebated lump-sum

\[ C_t + (1 + \tau) s_t O_t = w_t L_t + T_t \]  

(21)
Tax Analysis

Proportional subsidy to fringe oil production collected lump-sum

\[ C_t + s_t O_t = Y_t + \phi \tilde{I}_t \]  \hspace{1cm} (22)
Tax Analysis

Proportional tax on oil consumption with decreasing returns to scale

\[ \hat{O}_t = \hat{Z}_t \hat{X}_t^\gamma, \quad \hat{K}_t = 1 \]  (23)
Conclusions and future research

- The stylized facts of the oil market (oil production and price volatilities, spare capacity, etc) can be accounted for well quantitatively by a model of a dominant firm with competitive fringe
- The dominant oil producer represents a distortion which results in a loss of output and utility for oil-importing countries
- A simple proportional tax on oil consumption may not necessarily mitigate the distortion (depends on returns to scale)
- A proportional subsidy to fringe oil production may be welfare improving for oil importers