THE ECONOMIC JOURNAL

The Economic Journal, **123** (*December*), 1333–1362. Doi: 10.1111/ecoj.12031 © 2013 The Author(s). The Economic Journal © 2013 Royal Economic Society. Published by John Wiley & Sons, 9600 Garsington Road, Oxford OX4 2DQ, UK and 350 Main Street, Malden, MA 02148, USA.

SAUDI ARABIA AND THE OIL MARKET*

Anton Nakov and Galo Nuño

In this study, we document two features that have made Saudi Arabia different from other oil producers. First, it has typically maintained ample spare capacity. Second, its production has been quite volatile even though it has witnessed few domestic shocks. These features can be rationalised in a general equilibrium model in which the oil market is modelled as a dominant producer with a competitive fringe. We show that the net welfare effect of oil tariffs on consumers is null. The reason is that Saudi Arabia's monopolistic rents fall entirely on fringe producers.

Saudi Arabia is one of the largest players 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 reserves. The Kingdom is also a key OPEC (Organisation of Petroleum Exporting Countries) member, typically playing a central role in OPEC's decision-making. Indeed, authors such as Mabro (1975) have gone so far as to claim that 'OPEC *is* Saudi Arabia'. And according to Adelman (1995), 'the Saudis have acted as what they are: the leading firm in the world oil market'. Are these claims exaggerations? In this study, we document two features that have made Saudi Arabia different from the rest of the producers. First, it systematically restricts its production. In fact, its spare capacity is much larger than the aggregate spare capacity of the rest of the world's producers. Second, its production is quite volatile. The variance of Saudi oil output has been very high compared to that of the rest of the producers, even though the Kingdom itself has witnessed few domestic shocks affecting oil production directly.

We show that one can rationalise the behaviour of Saudi Arabia as that of a dominant producer with competitive fringe. In the spirit of Salant (1976), we build an industrial organisation model into a general equilibrium framework, assuming that the dominant supplier internalises the behavioural responses of fringe producers and oil consumers *à la* Stackelberg. Thus, Saudi Arabia understands and exploits the fact that its oil output and demand for inputs affects the supply of fringe producers, oil demand and the oil price. The result is that Saudi Arabia produces a smaller amount of oil than its capacity given the oil price, which allows it to charge a markup over its marginal cost.

We evaluate the model's performance relative to the data in one particular episode, the first Persian Gulf War. The model reproduces the more than 50% jump in the output of Saudi Arabia in response to the combined output collapse of Iraq and Kuwait quite well. From the point of view of our model, this behaviour of the dominant

* Corresponding author: Galo Nuño, European Central Bank, Kaiserstrasse 29, 60311, Frankfurt am Main, Germany. E-mail: galo.nuno@ecb.europa.eu.

Anton Nakov thanks the European Central Bank for its hospitality during the first drafts of this article. The views expressed here are those of the authors and do not necessarily coincide with the views of the the Eurosystem or the Federal Reserve System. We have benefited from comments and suggestions by Dirk Krueger, Lutz Kilian, Rafael Domenech, Alessia Campolmi and conference participants at ESSIM, Computing in Economics and Finance, Dynare, and seminar participants at Milano-Bicocca, ECB and BBVA.

supplier is entirely consistent with its own profit-maximising objective, as opposed to alternative non-economic (e.g. foreign policy) considerations.[1] It is optimal for the dominant supplier to increase its output substantially but not so much as to offset the output collapse of the fringe fully, so that the oil price rises in tandem with oil sales.

The existence of a dominant supplier with monopolistic power introduces a distortion in the oil market that potentially may affect households in oil-importing countries. This distortion could, in principle, justify the introduction of oil tariffs or other policy instruments by oil-importing countries in order to improve the welfare of their citizens by reducing the monopolistic rents extracted by the dominant supplier. Unlike partial equilibrium settings assuming an exogenous oil price, our framework is well suited for tracing the general equilibrium effects of these measures, working through the endogenously determined price of oil. This study shows that the net welfare effect on consumers of the dominant supplier is null. The reason is that all monopolistic rents fall on the competitive fringe and therefore the households of the oil-importing region are indifferent between a market with or without a dominant supplier. As a consequence we find that an oil consumption tax is not welfare improving.

We also show that technological advantage is a necessary condition for the profitable existence of the dominant supplier. This technological advantage allows Saudi Arabia to produce oil at lower costs and in a more elastic fashion, which reduces the volatility in oil prices and quantities. This is because the dominant supplier increases its market share when the oil price goes up, that is, when oil demand is high or competitive supply is low, and *vice versa*. Finally, we assess the desirability, from the point of view of the oil-importing region, of a subsidy to oil production by the fringe. We find that the optimal subsidy to fringe production is such that the oil price markup is completely eliminated and the oil price is significantly reduced.

The structure of the paper is as follows. In Section 1, we document the features that make Saudi Arabia different from the rest of the producers. In Section 2, we present the general equilibrium model. In Section 3, we simulate the dynamics of a calibrated version of the model and compare them with the historical data. In Section 4 we assess the welfare impact of several counterfactual scenarios and policy measures. And in Section 5 we conclude.

0.1. *Related Literature*

This study is related to three different strands of the literature. In first place, it relates to the large literature in energy economics about the structure of the oil market, and in particular, about the behaviour of OPEC.[2] A large portion of this literature suggests that the 'dominant supplier with competitive fringe' view of the oil industry is the one that best describes the empirical evidence. Examples include Mabro (1975), Dahl and Yücel (1991), Adelman (1995), Alhajji and Huettner (2000*a*, *b*) and Brémond *et al.*

[1] It does not mean that we discard any strategic consideration by Saudi Arabia when deciding its oil output. It only means that alternative explanations, such as the one outlined in this article, are also possible and complementary.

[2] This literature is large. A good review is Al-Qahtani *et al.* (2008).

(2011). In these studies, the role of the dominant supplier is played either by Saudi Arabia alone or together with Kuwait, UAE and Qatar ('the OPEC core'). This notwithstanding, the empirical evidence is not conclusive, as stressed by Smith (2005) or Almoguera *et al.* (2011). In contrast to this literature, our article does not formally test the market structure but presents two stylised facts – the large spare capacity of Saudi Arabia and the high volatility of its oil production – that can be explained *quantitatively* by assuming that Saudi Arabia is the dominant supplier in the market.

Second, our article relates to the literature on taxation or, more generally, public policy interventions in the oil market. Early works such as Bergstrom (1982) and Maskin and Newbery (1990) were mainly concerned with the exercise of monopsony power on the part of the importers, thus falling within the optimal tariff framework. Within the literature on optimal taxation – where the government of oil importing countries should raise revenues using different (potentially distortionary) tax instruments – Goulder (1994) analyses energy taxes taking into account the effect of environmental damage, Rotemberg and Woodford (1994) consider the impact of imperfect competition, and De Miguel and Manzano (2006) analyse the case of a small open economy. Finally, Karp and Newbery (1991) and Ulph and Folie (1981), discuss the possibility of time inconsistency in models with a dominant supplier with competitive fringe and a competitive set of importing countries.[3] In contrast to these studies, we focus on the static and dynamic welfare effects for the importers generated by the exercise of monopolistic power by the dominant oil supplier in a general equilibrium setting. In the same line, we analyse whether these potential distortions can (or should) be mitigated with diverse policy instruments, such as oil tariffs or subsidies to oil producers.

Third, this study relates to the literature on general equilibrium models that explicitly analyse the oil market. Recent progress includes studies by Leduc and Sill (2007) and Bodenstein *et al.* (2011), in which the oil price is determined endogenously while oil supply is given as an exogenous endowment. Backus and Crucini (2000) partially endogenise oil output by modelling it as the sum of two terms: an exogenous shock meant to represent unpredictable OPEC supply changes; and a term related to economic activity, which represents competitive oil supply. In contrast, in our model, as in Nakov and Pescatori (2010*a*, *b*), the oil market is characterised by the presence of a dominant oil supplier with competitive fringe.

Our model differs from Nakov and Pescatori (2010*a*, *b*) in three main dimensions: First, we consider a more detailed structure of oil producers, taking into account the process of capital accumulation in the oil industry.[4] Second, we take into account the distinct trends in oil production, oil price and the general economy. We do so by assuming a secular component of oil productivity to capture the fact that, over time, the cheaper sources of oil production are exhausted before the more expensive ones.

[3] See also 'Raise the Gas Tax' by Gregory Mankiw in *The Wall Street Journal*, 20 October 2006; as well as the 'Pigou Club Manifesto'. Mankiw explicitly makes the point that a consumption tax in the US might be useful for capturing some of the oil rents of Saudi Arabia.

[4] We also abstract from many details unrelated to the question analysed in this paper, such as sticky prices and monetary policy.

Third, we assume, in contrast to most of the previous literature, that oil is a final good that produces utility to the households in the importing country, instead of an input factor in the aggregate production function.

The assumption that oil is produced at a growth rate smaller than that of output is in line with the insights from the International Energy Agency (IEA 2008). It is meant to reflect the idea that there is a (quasi-) infinite amount of oil to be extracted at increasing marginal costs, in contrast to the traditional assumption that oil is a finite endowment that can be extracted at no cost. Indeed, in reality oil can be produced at increasingly higher marginal costs from several resources other than conventional crude, such as bitumen, oil shales, diverse gases and even coal.[5] Therefore, the total volume of resources that can be transformed into 'oil' at increasing marginal costs is very large compared to the current level of conventional oil reserves. In other words, as the world consumes more and more oil, there is no risk of running out of reserves, but of running out of 'cheap' reserves.

The inclusion of oil as a consumption good rather than as a factor of production is motivated by the recent empirical literature on the channels of transmission of oil price shocks to the economy. Kilian's (2008*a*) and Edelstein and Kilian's (2009) estimates suggest that the primary channel of transmission is through their effect on households' demand for goods and services, rather than as an input in production.[6] In the same line, Hamilton (2009) states that a key mechanism whereby energy price shocks affect the economy is through a disruption in consumers' and firms' spending on goods and services other than energy. Lee and Ni (2002) document how most US firms perceive energy price shocks as shocks to the demand for their products, rather that shocks to their production costs. Kilian and Park (2009) analyse the reaction of US stock returns to oil price shocks and find evidence that the transmission to the economy is driven not by domestic costs but by shifts in the final demand for goods and services.[7]

1. Is Saudi Arabia like the Other Producers?

In this Section, we analyse two particular features that make Saudi Arabia different from the rest of the oil producers. The first one is its large spare capacity and the second one the large volatility of its oil production.

1.1. *Spare Capacity*

If we take a closer look at the last four decades of oil market data what emerges is a picture of a granular oil industry. To take an example, the combined output of five of

[5] For example, during the Second World War Germany produced more than half of its oil supply from synthetic fuel derived from coal (see Yergin 1992).

[6] According to the IEA (2009), in recent years more than three quarters of global oil usage is in transportation and heating.

[7] De Miguel and Manzano (2006), Milani (2009) and Blanchard and Galí (2010) consider oil as an input factor *and* as consumption good in models with exogenous oil prices. However, in these models the short-run price-demand elasticity associated with the utility function is unity, whereas our model allows for any constant value of demand-elasticity. The importance of having a price elasticity of oil demand of less than one has been well established in the literature (Bodenstein, *et al.* 2011; Bodenstein and Guerrieri, 2011).

Table 1

Output and Spare Capacity of Main OPEC Producers (In Million Barrels Per Day)

	May 2001		May 2006		May 2011	
Country	Output	Spare capacity*	Output	Spare capacity*	Output	Spare capacity*
Algeria	0.81	0.13 (16%)	1.36	0.01 (1%)	1.28	0.06 (5%)
Iran	3.71	0.35 (9%)	3.84	0.16 (4%)	3.60	0.11 (3%)
Iraq	2.78	0.02 (1%)	1.91	0.60 (31%)	2.74	0.06 (2%)
Kuwait	2.00	0.56 (28%)	2.51	0.09 (4%)	2.44	0.10 (4%)
Libya	1.36	0.15 (11%)	1.70	0.00 (0%)	0.10	0.00 (0%)
Nigeria	2.00	0.21 (11%)	2.27	0.34 (15%)	2.32	0.21 (9%)
Qatar	0.67	0.12 (18%)	0.83	0.01 (1%)	0.81	0.21 (26%)
Saudi Arabia	*7.90*	*2.64 (33%)*	*9.35*	*1.45 (16%)*	*9.00*	*3.04 (34%)*
UAE	2.26	0.39 (17%)	2.56	0.15 (6%)	2.42	0.27 (11%)
Venezuela	2.83	0.26 (9%)	2.60	0.15 (6%)	2.46	0.18 (7%)

Note: *Numbers in parenthesis show spare capacity as a percentage of output.
Source. International Energy Agency 'Oil Market Report'.

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 (IEA, 2008). Focusing on Saudi Arabia's national oil champion, Aramco, it is 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-maximising price-taking framework.

Table 1 reports data about oil output and spare capacity for the main OPEC producers taken from the IEA 'Oil Market Report'. Spare capacity is defined as 'capacity levels that can be reached within 30 days and sustained for 90 days'. No data are provided by the IEA about non-OPEC producers, including Russia, since they are assumed to produce at full capacity. We have chosen to represent three points in the last 10 years. We complement it with Figure 1, which displays the evolution of spare capacity in the last decade for a subsample of the four largest OPEC producers (Saudi Arabia, Iran, Iraq and Venezuela).

Results indicate that Saudi Arabia maintains a large percentage of its production capacity idle. The Table reports values that range from 1/3 to 1/6. The average value of its spare capacity has been around 75% of its production. In comparison, the rest of producers, especially the large ones such as Iran, Iraq or Venezuela, have been producing very close to full capacity.[8] Here we have used standard measures of spare capacity from the IEA and Bloomberg. Nevertheless, according to other accounts such as Kilian (2008*b*) or Baumeister and Peersman (2012), spare capacity might have shrunk considerably in recent years. Even if that were the case, this does not detract from the fact that historically Saudi Arabia has had ample spare capacity.

[8] Iraq in the mid-2000s was an exception due to the war and the embargo.

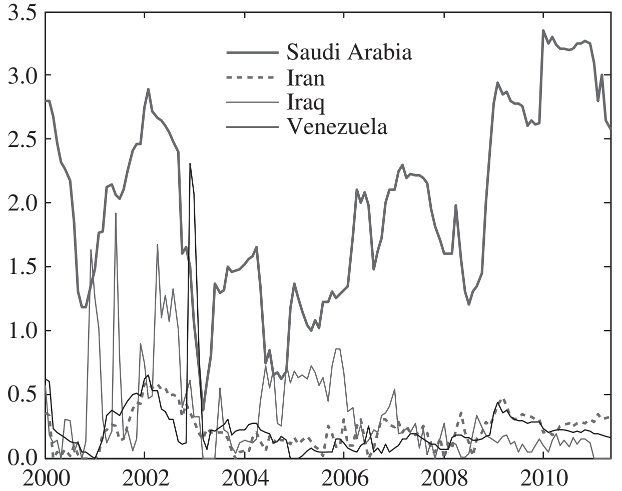

Fig. 1. *Spare Capacity of the Four Major OPEC Producers. In Million Barrels Per Day*
Source: Bloomberg.

1.2. *Volatility*

Table 2 reports data about the volatility in oil production. To construct this Table we have employed production data from the Energy Information Administration 'Monthly Energy Review'. Data span from January 1973 to May 2011. In the first three columns, we compute the production share as the production of each individual producer over the global production. In order to remove long-run trends, the data have been filtered using a band-pass filter *à la* Baxter and King (1999). The lower frequency is 1/180 cycles per month equivalent to a period of 15 years and the upper frequency is 2/5 cycles per month or two and half months.[9] Then we compute the standard deviation of the detrended share. In the last three columns we directly compute the standard deviation of the growth rates of production.

Results clearly show how Saudi Arabia's oil *output share* has been extremely volatile during the last four decades. Its standard deviation has been well above that of the rest of countries except Iraq in the period 1991–2011. In the case of growth rates, results are more heterogeneous as small producers, such as, Qatar, Norway or the UK are typically more volatile than large ones. Nevertheless, Saudi Arabia's oil production has been extremely volatile compared to other major oil producers. Its monthly standard deviation (6.6%) has been well above the one of USSR-Russia (1.3%) or the US (2.2%). In addition, the volatility of the aggregate growth rate of all producers except Saudi Arabia is 1.5% (data not shown in the Table), much less than the 6.6% of Saudi Arabia.

Although other large OPEC producers such as Iran, Iraq, Nigeria or Venezuela have displayed even larger growth rates volatilities, unlike Saudi Arabia these other countries experienced war, strikes, and political turmoil that directly affected their oil

[9] These long-run trends are present only at the invidual level in some producers due to the discovery of new reserves or to the progressive exhaustion of old oil fields. They cancel out at the aggregate level. We lose the first and last 3 years in the sampling process.

Table 2

Volatility of Production (%)

	Production share			Growth rate		
	Standard deviation*			Standard deviation		
Country	1973–2011	1973–91	1991–2011	1973–2011	1973–91	1991–2011
OPEC						
Algeria	0.10	0.12	0.07	4.36	6.08	1.13
Iran	0.88	1.25	0.16	14.85	20.93	2.32
Iraq	0.95	1.18	0.66	–	–	36.29
Kuwait	0.61	0.81	0.30	–	–	3.23
Libya	0.24	0.34	0.06	7.64	9.12	5.81
Nigeria	0.30	0.39	0.15	8.41	11.27	3.88
Qatar	0.07	0.09	0.04	12.96	18.02	3.62
Saudi Arabia	*1.31*	*1.78*	*0.51*	*6.63*	*9.18*	*2.03*
UAE	0.20	0.27	0.12	6.04	8.15	2.63
Venezuela	0.31	0.26	0.35	8.77	5.70	11.00
Non-OPEC						
Canada	0.13	0.14	0.12	5.47	7.08	3.15
China	0.12	0.14	0.10	3.04	4.03	1.52
Mexico	0.25	0.32	0.17	4.27	4.37	4.14
Norway	0.19	0.15	0.22	57.12	80.54	6.56
USSR	–	0.75	–	–	1.45	–
Russia	–	–	0.43	–	–	1.18
UK	0.28	0.30	0.26	37.19	52.10	6.91
USA	0.47	0.61	0.26	2.20	1.37	2.79

Note: *Filtered with a bandpass filter to remove the trend.
Source. Energy Information Administration 'Monthly Energy Review'.

production. Compared with these countries, Saudi Arabia was an island of stability. According to the US 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 during the Iraq–Iran conflict, and the attacks by Iraqi missiles during the first Gulf war in 1991. Apart from these episodes, most changes in Saudi oil production were the result of more or less rational decisions and not the consequence of disruptions in their production capabilities.

Figure 2 displays the oil market shares of the four major OPEC producers. The high volatility of Saudi Arabia's production compared to the other producers is clearly visible. In addition, sudden changes in the production of the other producers are the result of domestic shocks, such as the strikes in Iran or Venezuela or Iraq's wars, whereas in the Saudi case they cannot be attributed to any internal shock. Particularly striking is the case of the Persian Gulf war of 1990–1 where there is an abrupt fall in Iraq's production followed by a large increase in Saudi Arabia's output, not observed in other producers.

The conclusion is that Saudi Arabia, in contrast to the rest of OPEC and non-OPEC producers, systematically produces well below its capacity and moreover does so in a very volatile way.

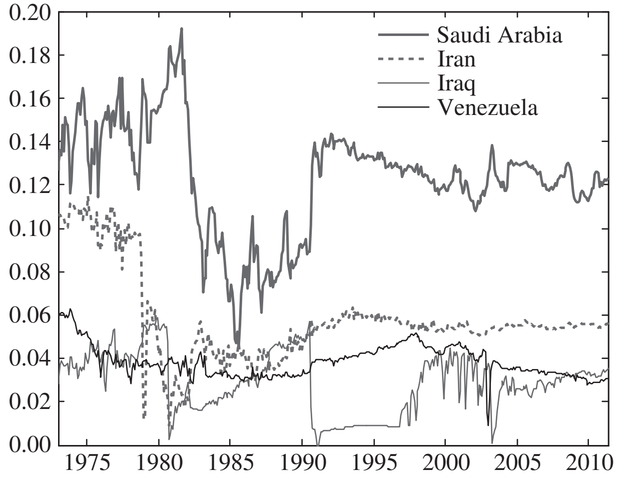

Fig. 2. *Market Shares of the Four Major OPEC Producers. Individual Production over World Production*
Source: Energy Information Administration.

2. Model

Our model of the global oil market comprises three regions: one oil-importing and two oil-exporting. The oil-importing region imports oil for use in consumption and employs labour and capital in the production of final goods, part of which are consumed domestically and the rest are exported to the two oil-producing regions.

Oil is a homogeneous commodity supplied by a dominant supplier and a fringe of competitive oil producers. The fringe take the oil price as given when choosing their production level. The dominant supplier faces a downward sloping residual demand curve and picks the profit-maximising points on that curve at each point in time and in each state of nature. 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.

Our model of the oil industry is in the spirit of Salant (1976) who used a similar structure to study the Nash–Cournot equilibrium in which the dominant supplier takes as given the output path of the fringe. Instead, we build this industrial structure into a general equilibrium framework, assuming that the dominant supplier is aware that it can manipulate the choices both of the competitive fringe and of the oil importer *à la* Stackelberg. For example, the dominant supplier understands that a change in its own oil supply will have an impact on oil demand, oil supply by fringe producers and the oil price. In order to provide more realism, we assume that the dominant supplier is a monopolist on the short-term residual demand but has information limitations regarding its long-term demand.

Except for the difference in market power, which is founded on a technological gap between the two types of oil producers, the competitive fringe and the dominant supplier are modelled symmetrically. This implies that, by appropriate choice of parameters of the oil production technology, our model spans the space from the extreme case of perfect competition to the opposite extreme of single monopoly. Our preferred calibration is one in which the dominant oil producer maintains an average market share of 12%, which corresponds roughly to the market share of Saudi Arabia since 1973.

2.1. *Oil-importing Region*

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

$$U(C, O, l) = \log(C) + v_t O^{1-\eta}/(1-\eta) - l^{1+\omega}/(1+\omega),$$

where η and ω are oil demand and labour supply elasticities.[10]

The household faces the period budget constraint

$$C_t + I_t + B_t + P_t O_t = w_t l_t + r_t^k K_{t-1} + r_{t-1} B_{t-1}, \quad (1)$$

which equates income from labour, $w_t l_t$, capital, $r_t^k K_{t-1}$ and bonds, $r_{t-1} B_{t-1}$, to outlays on consumption, C_t, capital investment, I_t, new one-period bonds, B_t and oil, $P_t O_t$; P_t denotes the real price of oil, while w_t denotes the real wage. We assume that all oil must be consumed within the period of production.[11]

Capital is accumulated according to

$$K_t = (1-\delta) K_{t-1} + I_t, \quad (2)$$

where δ is the depreciation rate of installed capital.

The household chooses C_t, O_t, B_t, I_t, K_t and l_t, to maximise expected present discounted utility

$$\max_{C_t, O_t, B_t, I_t, K_t, l_t} \mathrm{E}_o \sum_{t=0}^{\infty} \beta^t U(C_t, O_t, l_t),$$

subject to the budget constraint (1), where $0 < \beta < 1$ is a time preference parameter.

Final goods are produced with labour and capital by a representative price-taking firm, according to

$$Y_t = (Z_t l_t)^{\alpha} K_{t-1}^{1-\alpha}, \quad (3)$$

with $0 < \alpha < 1$. Aggregate total factor productivity Z_t follows an AR(1) process in log differences: $g_t^z = (1-\rho^z) g^z + \rho^z g_{t-1}^z + \varepsilon_t^z$, with $g_t^z \equiv \log(Z_t / Z_{t-1}), g^z = E(g_t^z)$ and ε_t^z is a Gaussian innovation with mean zero and variance σ_z^2.

Utility maximisation by households implies the following oil demand curve

$$v_t C_t = P_t O_t^{\eta}, \quad (4)$$

the labour supply curve

$$C_t l_t^{\omega} = w_t, \quad (5)$$

[10] We use capital letters for non-stationary variables and lower-case letters for stationary variables.

[11] 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 in pipelines or tankers. Relaxing this assumption to allow for delay between production and consumption does not affect significantly our main results.

and the Euler equations

$$1 = \beta \mathrm{E}_t \left\{ \frac{C_t}{C_{t+1}} [r^k_{t+1} + (1 - \delta)] \right\}, \tag{6}$$

and

$$1 = \beta \mathrm{E}_t \left(\frac{C_t}{C_{t+1}} \right) r_t. \tag{7}$$

Profit maximisation by price-taking firms implies the following labour demand

$$w_t l_t = \alpha Y_t, \tag{8}$$

and capital demand

$$r^k_t K_{t-1} = (1 - \alpha) Y_t. \tag{9}$$

The region's resource constraint states that total output, Y_t, must equal the sum of consumption, C_t, investment, I_t and current account, $(P_t O_t + B_t - r_{t-1} B_{t-1})$.

$$Y_t = C_t + I_t + (P_t O_t + B_t - r_{t-1} B_{t-1}). \tag{10}$$

2.2. *Competitive Fringe of Oil Exporters*

A representative household maximises the present discounted flow of utility from consumption,[12]

$$\max_{\tilde{C}_t, \tilde{I}_t, \tilde{B}_t, \tilde{K}_t} \mathrm{E}_o \sum_{t=0}^{\infty} \beta^t \log(\tilde{C}_t),$$

subject to the period budget constraint

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

where consumption, $\tilde{C}_t$ and investment, $\tilde{I}_t$, are both purchased from the oil-importing region, $\tilde{r}^k_t$ is the rental price of capital $\tilde{K}_t$ rented out by the household to oil firms, $\tilde{B}_t$ are one-period bonds that pay an interest of $\tilde{r}_t$ and $\tilde{D}_t$ are oil firm dividends rebated lump sum to the household.

The household invests in capital according to

$$\tilde{K}_t = (1 - \delta) \tilde{K}_{t-1} + \tilde{I}_t.$$

A representative fringe firm, owned by the household, maximises period profits

$$\tilde{D}_t = \max_{\tilde{X}_t, \tilde{K}_{t-1}} (P_t \tilde{O}_t - \tilde{X}_t - \tilde{r}_t \tilde{K}_{t-1}),$$

subject to the production technology

$$\tilde{O}_t = \tilde{Z}_t \tilde{u}_t \tilde{K}_{t-1}, \tag{11}$$

taking the oil price as given. $\tilde{Z}_t$ is the productivity of oil production and $(\tilde{u}_t \tilde{K}_{t-1})$ is the effective capital in the oil industry, defined as the product of capital utilisation $\tilde{u}_t$ and installed capital $\tilde{K}_{t-1}$. Productivity $\tilde{Z}_t = \tilde{a}_t \tilde{Z}_0 \exp(g^{\tilde{z}} t)$ follows an exogenous process

[12] We decorate variables belonging to the competitive fringe by tildes (e.g. $\tilde{X}_t$), and variables belonging to the dominant firm by hats (e.g. $\hat{X}_t$).

with a secular trend component $\tilde{Z}_0 \exp(g^{\tilde{z}} t)$, with $g^{\tilde{z}} < 0$, and a stationary AR(1) component in logs, $\log(\tilde{a}_t) = \rho_{\tilde{a}} \log(\tilde{a}_{t-1}) + \varepsilon_t^{\tilde{a}}$ with persistence $\rho_{\tilde{a}}$ and a Gaussian innovation $\varepsilon_t^{\tilde{a}}$ with mean zero and variance $\sigma^2_{\tilde{a}}$.[13] The downward trending component of oil productivity, $\tilde{Z}_0 \exp(g^{\tilde{z}} t)$, is introduced to capture the fact that, over time, the cheaper sources of oil production are exhausted before the more expensive ones.

We assume variable capital utilisation. In order to operate the installed capital, that is, to have a capital utilisation rate above zero, the representative fringe firm employs the intermediate good $\tilde{X}_t$ purchased from the oil-importing region and rents the capital $\tilde{K}_t$ from the household given a decreasing returns to scale function. The capacity utilisation rate of installed capital is given by

$$\tilde{u}(X, K) \equiv (X/K)^{\tilde{\gamma}}, \tag{12}$$

so that the oil production technology results in

$$\tilde{O}_t = \tilde{Z}_t \tilde{X}_t^{\tilde{\gamma}} \tilde{K}_{t-1}^{1-\tilde{\gamma}}. \tag{13}$$

Optimal oil supply by competitive fringe producers implies

$$\tilde{\gamma} P_t = \tilde{X}_t / \tilde{O}_t, \tag{14}$$

while optimal capital accumulation is given by

$$1 = \beta \mathrm{E}_t \left\{ \frac{\tilde{C}_t}{\tilde{C}_{t+1}} \left[(1-\tilde{\gamma}) P_{t+1} \frac{\tilde{O}_{t+1}}{\tilde{K}_t} + (1-\delta) \right] \right\},$$

and optimal bond-holding yields

$$1 = \beta \mathrm{E}_t \left(\frac{\tilde{C}_t}{\tilde{C}_{t+1}} \right) \tilde{r}_t.$$

Combining (13) and (14), the short-run supply curve is

$$\tilde{\gamma} P_t = \frac{\tilde{O}_t^{1/\tilde{\gamma}-1}}{\tilde{Z}_t^{1/\tilde{\gamma}} \tilde{K}_{t-1}^{1/\tilde{\gamma}-1}}. \tag{15}$$

The region's resource constraint is

$$P_t \tilde{O}_t = \tilde{C}_t + \tilde{I}_t + \tilde{X}_t + \tilde{B}_t - \tilde{r}_{t-1} \tilde{B}_{t-1}. \tag{16}$$

2.3. *Dominant Oil Exporter*

The dominant producer's economy has a structure symmetric to that of fringe producers, except that there is a single oil firm. The firm produces oil, $\hat{O}_t$, according to

$$\hat{O}_t = \hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}}, \tag{17}$$

using an imported intermediate good $\hat{X}_t$ and capital $\hat{K}_{t-1}$. We assume that the dominant supplier's technology evolves deterministically according to

[13] Note that the net growth rate of oil production TFP (total factor productivity) is negative. Increasing marginal costs of maintaining a given rate of extraction in the face of higher amounts of resource depleted (for the depletion effect, see e.g. Farzin (1992)) provide a potential rationale for negative TFP growth in oil production.

$\hat{Z}_t = \hat{Z}_0 \exp(g^{\hat{z}} t)$ where $g^{\hat{z}} = g^{\tilde{z}}$, that is, unlike the fringe, the dominant supplier's output is not directly affected by productivity shocks. Capital is accumulated 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 with the competitive fringe is that the dominant oil supplier has market power: it is aware of the dependence of fringe oil supply, of oil demand, and of the equilibrium oil price on its supply decision. We assume that the dominant supplier chooses a state-contingent plan which maximises the expected present discounted utility of its owners, subject to the demand by the oil-importing region, the supply of competitive fringe producers, and clearing in the oil market.

Thus, the decision problem of the dominant oil producer is

$$\max_{\hat{C}_t, \hat{B}_t, \hat{X}_t, \hat{K}_t, P_t} \mathrm{E}_o \sum_{t=0}^{\infty} \beta^t \log(\hat{C}_t),$$

subject to oil demand (4), fringe oil supply (15), its production technology (17), the oil market clearing condition

$$O_t = \hat{O}_t + \tilde{O}_t, \tag{18}$$

and its resource constraint

$$P_t \hat{O}_t = \hat{C}_t + \hat{K}_t - (1-\delta)\hat{K}_{t-1} + \hat{X}_t + \hat{B}_t - \hat{r}_{t-1}\hat{B}_{t-1}. \tag{19}$$

This amounts to assuming that while Saudi Arabia acts as a monopolist supplier of its residual demand in the short-run, it lacks information regarding the long-run (typically secret) investment plans of its competitors and the effect that its decisions may have on labour demand or capital accumulation in the oil-importing region.

The solution to the above problem under commitment yields the following first-order conditions (see Appendix B for details):

$$1 = \beta \mathrm{E}_t \left(\frac{\hat{C}_t}{\hat{C}_{t+1}} \right) \hat{r}_t,$$

$$\hat{\gamma}(P_t + \Lambda_t) = \hat{X}_t / \hat{O}_t,$$

$$1 = \beta \mathrm{E}_t \left\{ \frac{\hat{C}_t}{\hat{C}_{t+1}} \left[(1-\hat{\gamma})(P_{t+1} + \Lambda_{t+1}) \frac{\hat{O}_{t+1}}{\hat{K}_t} + (1-\delta) \right] \right\},$$

where Λ_t is the Lagrange multiplier associated with (18)

$$\Lambda_t = - \frac{P_t \hat{O}_t}{\left(\frac{1}{\eta} O_t + \frac{\tilde{\gamma}}{1-\tilde{\gamma}} \tilde{O}_t \right)}. \tag{20}$$

Notice that (20) can be also expressed as

$$\Lambda_t = - \frac{\hat{O}_t}{\left(\frac{O_t}{P_t} \Phi_D + \frac{\tilde{O}_t}{P_t} \Phi_S \right)},$$

where $\Phi_D \equiv -(P_t/O_t)(\partial O_t/\partial P_t) = 1/\eta$ is the short-run oil demand elasticity from (4) and $\Phi_S \equiv (P_t/\tilde{O}_t)(\partial \tilde{O}_t/\partial P_t) = \tilde{\gamma}/(1-\tilde{\gamma})$ is the short-run fringe supply elasticity from (15).

The dominant oil supplier extracts a pure rent by picking the profit-maximising point on the residual demand curve, where marginal revenue equals his marginal cost. Thus, one can derive

PROPOSITION 1. *The steady-state price mark-up of the dominant oil producer is given by*

$$\mu \equiv \frac{P}{\widehat{MC}} = \Upsilon r^{\hat{\gamma}-\tilde{\gamma}}, \tag{21}$$

where $\widehat{MC}$ *is the marginal cost of the dominant supplier's oil firm,* $r = g_z/\beta + \delta - 1$ *is the steady-state return on capital used in oil production and* $\Upsilon \equiv \hat{Z}_0\hat{\gamma}^{\hat{\gamma}}(1-\hat{\gamma})^{1-\hat{\gamma}}/[\tilde{Z}_0\tilde{\gamma}^{\tilde{\gamma}}(1-\tilde{\gamma})^{1-\tilde{\gamma}}]$ *is the steady-state technological advantage of the dominant supplier over the fringe.*

Proof. See Appendix A.

COROLLARY 1. *In the case in which* $\tilde{\gamma} = \hat{\gamma}$ *(the two technologies are symmetric), a dominant producer can exist profitably as long as it enjoys an average cost advantage,* $\hat{Z}_0 > \tilde{Z}_0$.

Proof. See Appendix A.

COROLLARY 2. *When* $\tilde{\gamma} = \hat{\gamma}$, *the degree of competition is related to the size of the technological gap* $\tilde{Z}_0/\hat{Z}_0 \in [0,1]$. *As* $\tilde{Z}_0/\hat{Z}_0 \longrightarrow 1$, *the model approaches perfect competition in oil production.*

The oil market share of the dominant producer can be expressed as a function of the short-run supply and demand elasticities and the mark-up:

PROPOSITION 2. *The steady-state oil market share of the dominant producer is given by*

$$\frac{\hat{O}}{O} = \frac{\Phi_S + \Phi_D}{\Phi_S - \mu}.$$

Proof. See Appendix A.

2.4. *Market Clearing and Balanced Growth Path*

In equilibrium, all markets clear. For simplicity, we assume financial autarky and thus[14]

$$B_t = \tilde{B}_t = \hat{B}_t = 0. \tag{22}$$

[14] However, we have also analysed alternative possibilities, such as considering each region as a small open economy, and results do not change qualitatively. Results are available upon request.

Oil market clearing is

$$O_t = \hat{O}_t + \tilde{O}_t. \tag{23}$$

And goods market clearing is

$$Y_t = C_t + I_t + \tilde{C}_t + \tilde{I}_t + \tilde{X}_t + \hat{C}_t + \hat{I}_t + \hat{X}_t. \tag{24}$$

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 (v_t). Stationarity of Saudi Arabia's market share requires $g^{\tilde{z}} = g^{\hat{z}}$. In a steady-state with balanced growth, the ratio $P_t O_t / Y_t$ must remain stationary. Given $g^{\tilde{z}} = g^{\hat{z}}$, since O_t grows at rate $g^z + g^{\tilde{z}} = g^z + g^{\hat{z}}$, while Y_t grows at rate g^z, for the ratio $P_t O_t / Y_t$ to remain stable, P_t should grow at rate $-g^{\tilde{z}}$. This leads to the following

Proposition 3. *The real price of oil grows at rate* $-g^{\tilde{z}} > 0$ *over time.*

Similar to Hassler *et al.* (2010), we assume that the oil-importing country constantly improves its oil efficiency, captured by a secular upward trend in v_t. The existence of a 'balanced growth path', in which the share of oil expenditure in gross domestic product (GDP) remains stable, requires a particular value for the rate of change of v_t.

Condition 1. *Oil efficiency* v_t *grows at rate* $(\eta - 1)(g^z + g^{\tilde{z}})$.

The variable v_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, $v_t C_t = P_t O_t^{\eta}$. Along the balanced growth path, C_t grows at rate g^z while $P_t O_t^{\eta}$ grows at rate $\eta(g^z + g^{\tilde{z}}) - g^{\tilde{z}}$. Hence, along the balanced growth path v_t must grow at rate $(\eta - 1)(g^z + g^{\tilde{z}})$. Since in the data the trend in oil production is positive, $(g^z + g^{\tilde{z}}) > 0$, for values of $\eta > 1$, energy efficiency must increase over time. In particular, we assume that oil efficiency takes the form

$$v_t = v_0 (Z_t e^{g^{\tilde{z}} t})^{\eta - 1},$$

which satisfies the previous condition.

Finally, as discussed in Section 1, capacity utilisation in the data is computed as the ratio of actual output to 'sustainable production capacity', where the latter is defined as the production level that can be reached within 30 days and sustained for 90 days. In the model, the capacity utilisation of the dominant supplier is defined as the use of its installed capital, given the oil production technology. This amount is normalised by the corresponding use of capital by competitive producers, who are assumed to operate at 100% of capacity. Using the above definition, we can derive an expression for the capacity utilisation of the dominant oil producer *relative* to that of the competitive fringe,

$$u(\hat{X}, \hat{K}) / u(\tilde{X}, \tilde{K}) = (\hat{X}/\hat{K})^{\hat{\gamma}} / (\tilde{X}/\tilde{K})^{\tilde{\gamma}}. \tag{25}$$

3. Oil Market Dynamics

In this Section, we analyse whether the model can reproduce the observed volatility in the production of Saudi Arabia. To this end, we calibrate the model to replicate certain moments observed in the data and then analyse the counterfactual volatility of Saudi Arabia's production. In order to gain further insight, we analyse the impulse responses and we study a particular episode (the First Gulf War) in light of the model. We show how the extreme volatility of Saudi Arabia's oil production can be explained as the rational response of a dominant supplier facing stochastic changes of the oil demand and of the competitive supply.

3.1. *Calibration*

The baseline calibration is shown in Table 3. The working frequency of our model is monthly. We calibrate the trend and time preference parameters as follows. The secular growth rate of technology of the oil-importing region is set to $\exp(g^z) = 1.03^{1/12}$, consistent with an average world output growth rate of 3% per year for the period from 1973 to 2009. Given this, we set the time preference parameter to $\beta = 1.01^{-1/12}$ equivalent to an average real interest rate of 4% per year.

Based on the stationary market share of Saudi Arabia in the data, we impose equality between the growth rates of the dominant oil producer and the fringe, $g^{\hat{z}} = g^{\tilde{z}}$. The average growth rate of total oil production is 0.8% per year in the data. In the model this must equal the sum of the growth rate of the inputs of oil production, g^z and the growth rate of the oil production technology itself, $g^{\tilde{z}}$, implying a value for $\exp(g^{\tilde{z}}) = 0.9982$ on a monthly basis. Given Proposition 3, the latter implies that

Table 3
Calibration

Parameter	Value		Target
	High-elasticity	Low-elasticicty	
g^z	$\log(1.03^{1/12})$		Average world output growth rate of 3% per year
β	$1.01^{-1/12}$		Average real interest rate of 4% per year
$g^{\hat{z}}, g^{\tilde{z}}$	log (0.9982)		Average growth rate of total oil production of 0.8% per year
ω	1		Unit Frisch elasticity
α	0.67		US labour share
δ	$1.10^{1/12} - 1$		10% annual depreciation of installed capital
$\tilde{\gamma}$	0.4		SA price mark-up of 25%
ρ_Z	0.944		Half-life of the oil demand shock of one year
$\rho_{\tilde{a}}$	0.944		Half-life of the oil supply shock of one year
σ_Z	0.004		Total output volatility 2%
η	4	21	Short-run price elasticity of oil demand of 0.25 or 0.05, respectively
$\hat{Z}_0$	1.8617	1.9838	Oil share of 5% of GDP
$\hat{\gamma}$	0.4384	0.5	SA global market share of 12%
v_0	0.0087	2.5092×10^{-10}	SA capacity utilisation of 75%
$\sigma_{\tilde{a}}$	0.05	0.04	Oil price volatility 8%

the real oil price must grow at an annual rate of 2.2%, which is consistent with the average growth rate actually observed in the data.

Second, we set three parameters governing the oil-importing region's labour disutility, technology and capital depreciation, to their typical values in the RBC literature: the inverse Frisch elasticity is set to $\omega = 1$, the labour share in the production of final goods is set to $\alpha = 0.67$; and the depreciation rate is set to $\delta = 1.10^{1/12} - 1$, consistent with 10% annual depreciation of installed capital.

Third, the price elasticity of oil demand in the model is $(P/O)(\partial O/\partial P) = (1/\eta)$. There is a certain disagreement in the literature about the value of this parameter. We consider two possibilities. First, we set $\eta = 4$, consistent with Kilian and Murphy's (2010) estimates of the short-run price elasticity of oil demand of about 0.25. We also consider the alternative case $\eta = 21$, following Smith's (2009) estimates of the short-run price elasticity of oil demand of about 0.05. We denote the first case as 'high demand elasticity' and the second one as 'low demand elasticity'.

Fourth, we calibrate v and the parameters of the two oil production technologies $(\tilde{Z}_0, \hat{Z}_0, \tilde{\gamma}, \hat{\gamma}, v_0)$ jointly as follows. We normalise the initial level of productivity of the fringe to $\tilde{Z}_0 = 1$. We then search for a vector $(\hat{Z}_0, \tilde{\gamma}, \hat{\gamma}, v_0)$ which allows the model to match an average 'oil share in spending' of 5% of GDP, as well as the following three averages for Saudi Arabia: a global market share of 12.3%, capacity utilisation of 75% and a price mark-up of 25%. We should stress that our measure of marginal costs includes not only the intermediate input costs but also capital rents. The targets for Saudi Arabia are calculated in the following way. The average market share is computed directly from data on oil output provided by the Energy Information Administration for the period from January 1973 to April 2009. The capacity utilisation rate is estimated around 75% based on data from IEA (2008, 2009). Data on the average markup are hard to obtain but we assume it to be around 20% based on estimates of long-run marginal costs provided by IEA. This number is also in line with estimates of the marginal revenue of OPEC members cited by Smith (2009), who considers it a lower bound for the marginal revenue of Saudi Arabia. We are able to approximate these four targets well by setting $\tilde{\gamma} = 0.4$ and, for the high-elasticity case, $\hat{Z}_0 = 1.8617$, $\hat{\gamma} = 0.4384$, $v_0 = 0.0087$, or $\hat{Z}_0 = 1.9838$, $\hat{\gamma} = 0.5$, $v_0 = 2.5092 \times 10^{-10}$for the low-elasticity case.

Finally, in order to analyse the dynamics, we parameterise the two shock processes as follows.[15] We pick values for the autoregressive coefficients which are consistent with a half-life of one year, $\rho_Z = 0.944$ and $\rho_{\tilde{a}} = 0.944$, which is equivalent to 0.5 on an annual basis. This may overstate somewhat the persistence of the *growth rate* of US TFP but we really mean the demand shock to represent a persistent TFP increase in developing countries such as China, not the US. We then set the standard deviations of the two innovations to $\sigma_Z = 0.004$ and $\sigma_{\tilde{a}} = 0.05$ (0.04 for the low-elasticity case) so as to match the monthly standard deviations of the log-difference of the real oil price, and of total oil output.

[15] Ideally, one would like to estimate these processes from the data. Computing them as Solow residuals is subject to well-known difficulties related to the correct measurement of inputs. On the other hand, a full-blown Bayesian estimation of the model is beyond the scope of this study.

Table 4

*Data and Model Standard Deviations**

	Oil price	Oil output	Fringe output	Saudi output
Data	8.5	1.6	1.5	6.6
Model				
High elasticity	8.1	2.2	3.3	6.5
Low elasticity	8.3	1.2	1.7	6.4

Note: *Standard deviations, in percentage points, of first log differences.

3.2. *Explaining the Volatility of Saudi Arabia's Output*

Table 4 summarises the fit of our model to relevant second moments of the data. The four series of interest are: the log-differences of total oil output, of Saudi Arabia's oil output and of the fringe oil output and the log-difference of the real oil price.[16] The key point is that the model is successful at reproducing the observed volatility of the growth rate of Saudi Arabia's production computed in Table 2 even if Saudi Arabia is not affected by any domestic shock to its production.

Figure 3 shows the general equilibrium responses of several variables of interest to each of the two shocks. We display the results only for the high-elasticity calibration, as they are qualitatively similar in both cases. The dashed line shows the responses to a one-standard deviation drop in the productivity of the fringe. This is an example of a transitory 'negative oil supply shock' with a half-life of one year. As a result, the oil output of the fringe falls by 3% on impact, while the output of the dominant oil producer increases by as much as 6%, raising its market share by around 1 percentage point. The increased production of the dominant oil supplier is not sufficient to offset the output decline of the fringe fully; hence, total oil supply falls by around 2%, while the oil price rises by 8%. These impulse–responses are in line with the observed behaviour in episodes of 'negative oil supply shocks', for instance during the Iranian revolution and during 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.

The solid lines in Figure 3 show the responses to a type of 'positive oil demand shock', namely an unexpected one-standard deviation rise in the *growth rate* of TFP of the oil-importing region, resulting in a permanent rise of the *level* of TFP.[17] As a consequence of this shock, the output of the oil-importing region rises gradually towards its new, higher, balanced growth path, as does oil consumption. The oil price at first rises gradually, peaks at 4% above its balanced growth path around two years after the initial impulse and then decays back towards its steady-state path. Both the

[16] Data on oil supply 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 US CPI. Data on the nominal oil price and US CPI, are taken from the FRED II online database.

[17] There can be other types of demand shocks. Bodenstein and Guerrieri (2011), for example, show that much of the demand since 2003 did not come from TFP but from changes in oil intensity, which in our study would be associated with changes in v_t. Kilian (2009) discusses how changes in TFP are not enough to explain changes in oil demand.

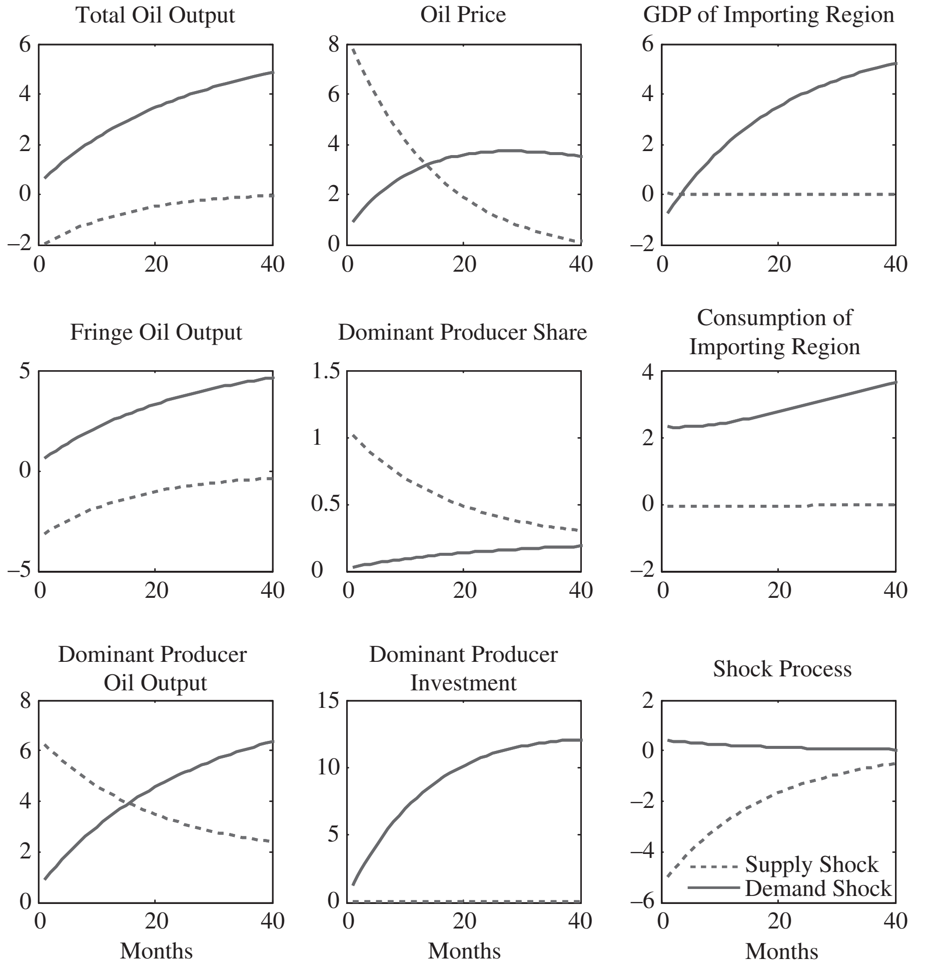

Fig. 3. *Impulse Responses to an Oil Supply and Oil Demand Shock*

fringe oil producers and the dominant oil supplier increase their output, although the dominant producer does so a bit faster, so that its market share slightly increases. These responses are consistent with episodes of (negative) oil demand shocks such as the dotcom bust and the sub-prime crisis. In both cases Saudi Arabia reduced its oil output significantly in response to dwindling global demand and a falling oil price. In contrast to the supply shock, in this case the oil price rise is associated with a rise in the GDP of the oil-importing region following the cumulative rise in its TFP. As pointed out by Kilian (2009) and Nakov and Pescatori (2010*a*), it is natural that different fundamental shocks should induce different co-movement between the oil price, oil supply and the GDP of the oil-importing region.

The exercises above build confidence that profit maximisation on behalf of the dominant producer with spare capacity goes a long way towards explaining why Saudi Arabia increases its output strongly in response to supply disruptions elsewhere, while it reduces its production aggressively when oil importers are hit by a recession.

3.3. *Event Study: The Persian Gulf War of 1990–1*

In this subsection, we analyse how well our model can account quantitatively for a particular episode that can broadly be seen as a supply shock: the first Gulf War.

In August 1990, Iraq invaded Kuwait on the pretext that Kuwait was stealing oil across the border by 'slant-drilling' into Iraq's Rumaila oil field. Because of the war and the trade embargo imposed by the UN, the combined oil supply of the two countries fell by more than 5.3 million barrels per day (mbd), while the oil price surged from \$19 per barrel in July to \$34 per barrel in September 1990. The reaction of Saudi Arabia was quite powerful: it raised its own oil production from 5.4 mbd in July 1990 to 7.6 mbd in September, and to 8.4 mbd by the end of 1990, a 56% increase in just a few months! Other major oil producers did not increase their production significantly: Iran and the US increased their oil output by only 0.2 mbd, while the Soviet Union actually reduced its production. A similar pattern of collapsing Iraqi oil supply accompanied by a sizable increase in Saudi Arabia's oil output was observed also in the second Persian Gulf war of 2003.

The prevailing hypothesis for the decision of Saudi Arabia to increase its own oil supply drastically is that it was based on non-economic considerations, such as the desire to support the already flagging US economy facing a war with Iraq (Yergin, 1992). Yet, as we saw in Figure 3, this same behaviour of increasing its own supply (but not enough to fully offset the impact of the initial shock on the oil price), is also consistent with the purely economic objective of profit maximisation by the dominant supplier. Indeed, given a negative supply shock experienced by the fringe, it is optimal for the dominant supplier to let profits rise through a combined increase of both the oil price and the quantity of oil sold.

In Figure 4 we assess the ability of our model to account for this episode quantitatively. In particular, we use a Kalman filter based on the state-space linear solution of the model to estimate a sequence of shocks to fringe productivity such that the fringe oil output predicted by the model matches its actual amount in the data exactly (see the top left panel). We then contrast the actual with the model-implied evolution of Saudi Arabia's oil output, total oil production and the real price of oil.

The Figure illustrates that the model is successful at predicting the surge in Saudi Arabia's oil production and the fact that this surge was less than sufficient to prevent a decline in total oil output.[18] This is particularly true for the model with low demand elasticity ($\eta = 21$). As for the oil price, in the case of low-demand elasticity, the model predicts the initial jump from around \$20 to around \$35 per barrel well; after that, however, the model predicts that the oil price would remain around \$35 while the actual oil price gradually fell back to \$20 in the course of the year. In the case of high-demand elasticity, the pattern is similar but the oil price only increases to \$28. Part of the explanation for the subsequent decline of the oil price observed in the data may be the US recession from July 1990 to March 1991. This is consistent, from the point of view of our model, with an

[18] Due to its simplicity, the model fails to capture the lag in the response of Saudi oil production after the decrease of the fringe oil output.

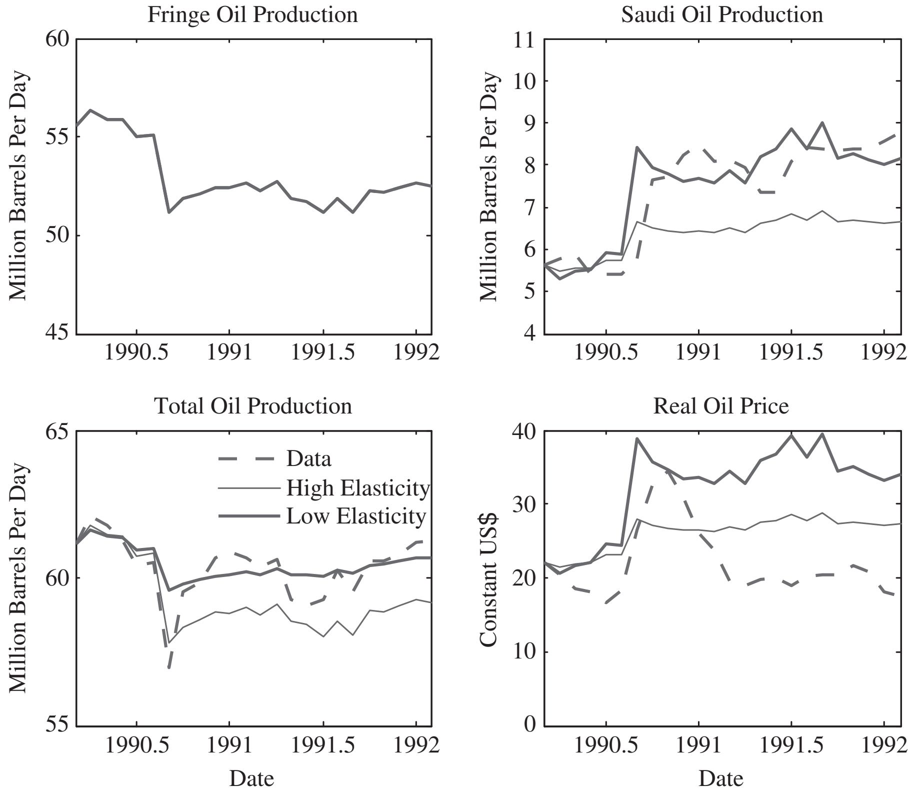

Fig. 4. *Oil Output and Prices during the 1991 Gulf War*

autonomous drop in US TFP, a channel which we have deliberately shut down in this exercise.[19]

The fact that we are able to explain the behaviour of Saudi Arabia as a dominant supplier does not imply that we reject additional explanations based on geopolitical reasons. Probably various factors contributed. However, if Saudi Arabia *is* the dominant supplier in the oil market, this may have important welfare implications for other countries, an issue which we explore in the next Section.

4. The Economic Consequences of Saudi Arabia

In this Section, we explore the consequences of the presence of a dominant supplier in the oil market. First we analyse two counterfactual scenarios with a competitive oil market. Then we analyse whether it is possible to improve the welfare of households in the oil-importing countries by two policy interventions in the oil market. All of the following results are qualitatively similar for both cases of high and low oil demand elasticities. For brevity, we only report results for the high elasticity case ($\eta = 4$).

[19] Alquist and Kilian (2010) and Kilian and Murphy (2010) have stressed the speculative demand shock component of that price increase, which may help explain why the model with high-demand elasticity fails to fully account for the increase in the oil price and in Saudi Arabia production.

4.1. *Welfare Analysis*

Table 5 displays the comparison among three different scenarios. In the first column, we present the 'baseline' calibration described in the previous Section. In the second column ('competitive market – standard production'), we analyse a case in which Saudi Arabia loses its technological advantage in oil production with respect to the other producers. In particular, we assume that $\hat{\gamma} \to \tilde{\gamma}$ and $\hat{Z}_0 \to \tilde{Z}_0$. In this case, Saudi Arabia becomes an atomistic price-taker who cannot influence the oil price. The oil market is thus competitive. Finally, in the third column ('competitive market – superior production'), we consider the alternative case in which the reason why Saudi Arabia has no advantage with respect to the other producers is because the other producers are endowed with the same low-cost production technology, that is, $\tilde{\gamma} \to \hat{\gamma}$ and $\tilde{Z}_0 \to \hat{Z}_0$.

Comparing the baseline with the 'standard production' scenario it turns out that, in the steady-state, the presence of a dominant supplier does not affect the oil-importing country. Consumption, employment and oil imports are the same with and without the dominant supplier. The main welfare losers are competitive fringe's households, as they lose 14% of consumption-equivalent welfare due to the presence of Saudi Arabia. This means that, in the steady-state, the oil importing region is indifferent between the baseline market and a perfect competition setting in which Saudi Arabia cannot produce oil cheaper than the rest of producers. This is because competitive fringe households are the ones that bear the burden of the monopoly.

Introducing the superior production scenario allows us to analyse the effect of cheaper oil production. If competitive fringe oil firms were able to produce oil with the same production technology as Saudi Arabia, they would again drive it out of the market. However, the steady-state equilibrium in this case would be welfare-improving for the oil importers. Oil prices would fall 15% with respect to the balanced-growth

Table 5

Welfare and Volatility Analysis (%)

		Competitive market	
	Baseline	Standard prod.	Superior prod.
Balanced growth path			
Consumption*	–	0	0.42
Oil price*	–	0	−14.74
Oil output*	–	0	4.17
Welfare†	–		
Importing country	–	0	1.15
Competitive fringe country	–	14.02	−15.60
Volatilities			
GDP	1.34	1.34	1.34
Employment	7.31	7.33	7.30
Oil price	8.05	9.32	8.84
Oil output	2.24	2.53	2.43

Notes: *Percentage changes from the steady state in the baseline scenario. †In consumption equivalent terms with respect to steady state in the baseline scenario.

trend, allowing an increase in oil consumption of 4%. This would imply an increase in consumption of 0.4% and an equivalent rise in welfare of 1.1% in consumption terms. However, in this case, households in the competitive fringe would lose 16% of consumption due to the negative change in their terms of trade.

Looking at volatilities we see how the presence of Saudi Arabia reduces the volatility of oil prices and quantities compared to the other two scenarios. This volatility reduction is a consequence of Saudi Arabia's monopolistic behaviour. In essence, Saudi Arabia introduces a monopolistic mark-up on the rest of producers and at the same time it helps to reduce the volatility in the oil market by acting as a swing producer.

4.2. *Oil Taxes and Subsidies in General Equilibrium*

Finally, we turn to the question of policy. We have seen that, in the steady-state, the presence of a dominant oil supplier forces a markup distortion on the oil market. Although this distortion does not reduce the welfare of the oil-importing region, a natural question is whether this region can adopt any suitable fiscal policies to increase its welfare in an imperfectly competitive oil market. One possible policy is raising a tax on oil consumption; another is giving an investment subsidy to fringe oil producers. Here we analyse these possibilities from the perspective of our general equilibrium model. Since the equilibrium oil price, oil supply and demand are all likely to be affected by any oil taxes or subsidies, our model, which endogenously determines these variables, is better suited to addressing the question of tax incidence than partial equilibrium frameworks which take the oil price or oil supply as given.

4.2.1. *Oil consumption tax*

To study the effects of a proportional tax on oil consumption, we modify the budget constraint of the households of the oil-importing region as follows

$$C_t + I_t + B_t + (1+\tau)P_t O_t = w_t l_t + r_t^k K_{t-1} + r_{t-1} B_{t-1} + T_t, \tag{26}$$

where $(1+\tau)P_t$ is the price of oil paid by the consumer and $T_t = \tau P_t O_t$ is a lump-sum rebate.

In general, it is not clear *a priori* how the burden of the tax is shared between oil consumers and oil producers. It is possible, at least in principle, 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.

Indeed, we find that oil consumption is discouraged by a positive oil consumption tax (see Figure 5). Resources previously used for oil consumption are now redirected to more final goods consumption and leisure. However, the fact that final goods consumption increases while labour hours are reduced does not necessarily imply that welfare rises. Indeed, the utility gain from increased goods consumption and leisure is more than offset by the loss of utility from less oil consumption. In this case, it turns out that the burden of the tax falls entirely on consumers. 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 model, the optimal oil consumption tax is zero from a welfare

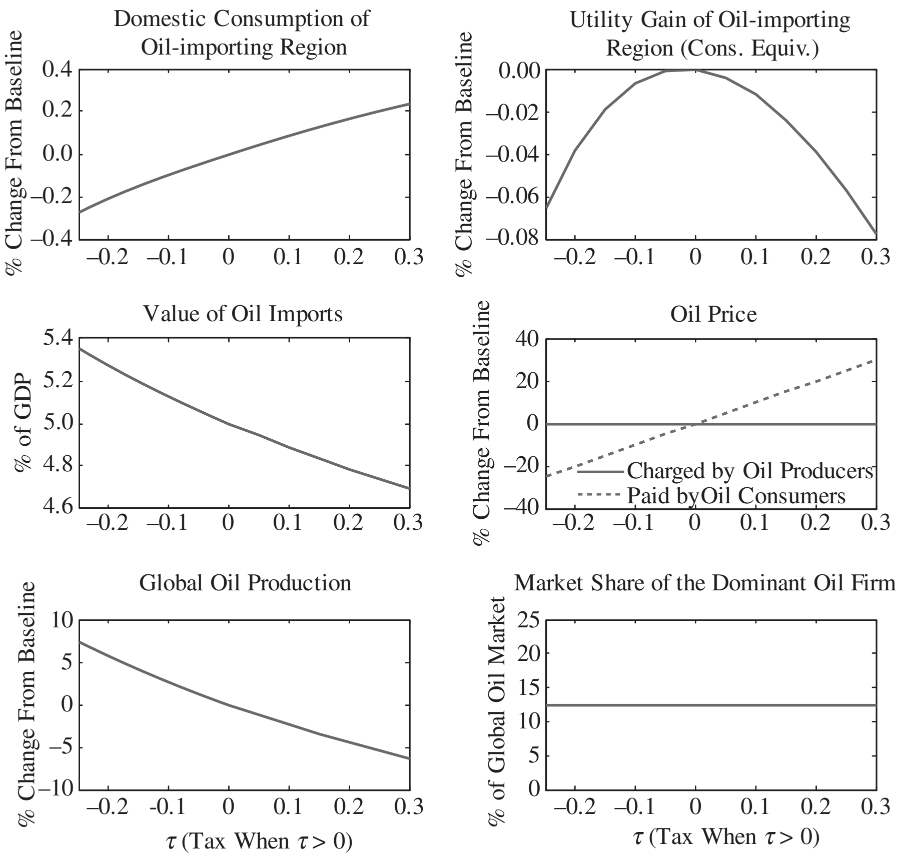

Fig. 5. *The Effects of an Oil Consumption Tax*

point of view, despite the fact that final goods consumption increases while hours worked fall with a positive tax.

These results should be of no surprise after the results displayed in Table 5. As oil-importing countries are not affected by the presence of the dominant supplier, a distortionary tax on oil is suboptimal for them.

4.2.2. *Fringe investment subsidy*

We also analyse the case of an oil production subsidy. The latter might work by offsetting what is effectively an oil production tax: the presence of a dominant supplier supplying less oil than the competitive level despite lower costs. The way we implement it 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 becomes

$$\tilde{C}_t + (1+\phi)\tilde{I}_t = \tilde{r}_t\tilde{K}_{t-1} + \tilde{D}_t + \tilde{B}_t - \tilde{r}_{t-1}\tilde{B}_{t-1}, \tag{27}$$

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

$$C_t + I_t + B_t + P_t O_t = Y_t + r_{t-1} B_{t-1} + T_t, \tag{28}$$

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

Notice that, in principle, such a subsidy can eliminate completely the oil profits of the dominant supplier:

PROPOSITION 4. *The oil price markup can be eliminated completely by subsidising the capital investment of competitive fringe producers. The subsidy which achieves this is*

$$\bar{\phi} = \Upsilon^{-1}[g_z/\beta - (1-\delta)]^{\frac{\tilde{\gamma}-\hat{\gamma}}{1-\tilde{\gamma}}} - 1. \tag{29}$$

Proof. See Appendix A.

Figure 6 shows that the maximum welfare is achieved for an oil production subsidy of about 23% of the price of investment ($\bar{\phi} = -0.23$). The subsidy works by lowering the cost of oil production by the competitive fringe, increasing the global oil supply and lowering the market share of the dominant supplier. In fact, the optimal level is

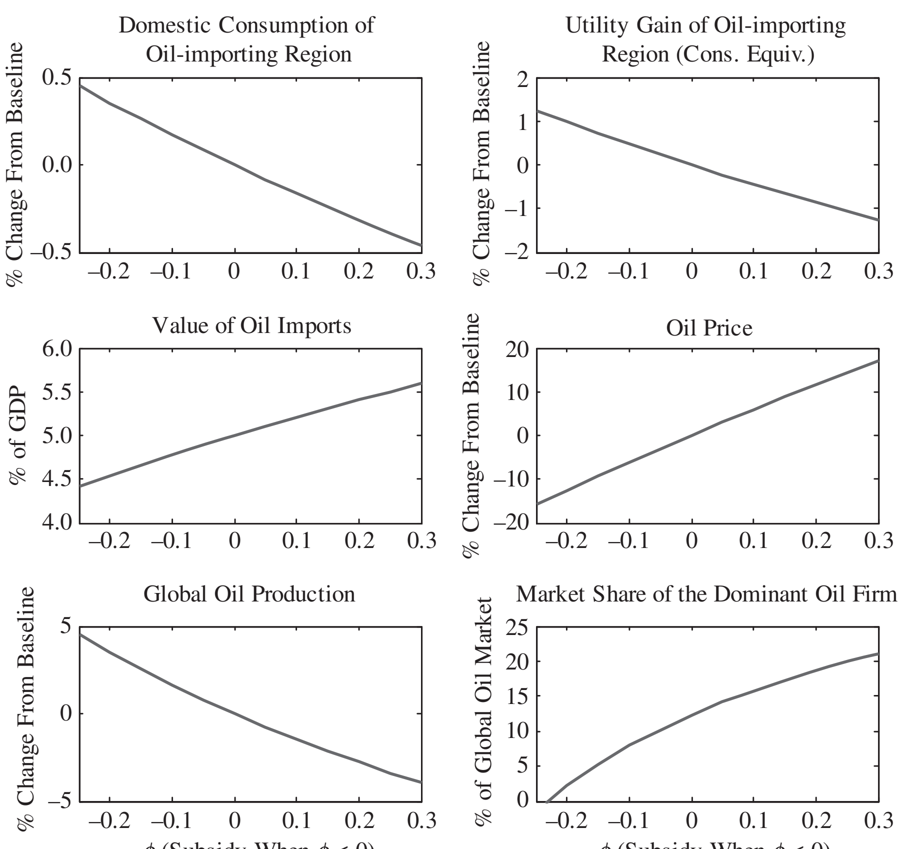

Fig. 6. *The Effects of Subsidy to Fringe Investment*

such that the oil price markup is completely eliminated and the market share of the dominant producer is null. The net gains for the oil-importing region of this policy are significant: around 0.5% in terms of domestic consumption, or a net welfare gain equivalent to a permanent increase of consumption by 1.2%, when accounting for the changes in oil consumption and hours worked.

5. Conclusions

A closer look at the international oil market reveals an industrial structure which is quite different from the perfect competition paradigm. A single country accounts for more than 10% of global oil supply. This country maintains ample spare capacity and high volatility of its oil production. We show that these facts can be accounted for quantitatively by a fairly standard model of a dominant supplier with competitive fringe. In our model, it is in the dominant suppliers' own interest to increase output when fringe production is hit by a negative shock. The offsetting is incomplete by design, as it is optimal to let the oil price rise in tandem with the dominant supplier's oil output.

We use our model to quantify the distortion from the presence of a dominant oil supplier. We show how the dominant supplier charges a mark-up over its marginal cost, thus distorting the market. However, households in the oil-importing country are not affected in steady-state by the presence of the dominant supplier, as all the monopolistic rents are paid by the competitive fringe. The consequence is that a tax/subsidy on oil consumption is not welfare-improving for the importers.

Importantly, our analysis of oil taxation ignores several important features of the market. In particular, it abstracts from the environmental impact of oil usage, the possibility of developing alternative energy sources or the financial linkages among oil exporters and importers. Introducing some of these features might modify our policy conclusions. We leave these questions for future research.

Finally, it remains to be seen whether Saudi Arabia's cost advantage will be sustainable in the future, allowing it to have spare capacity and to continue playing the role of a dominant supplier in the oil market.

Appendix A. Proofs

A.1. *Proof of Proposition 1*

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,

$$P_t = \widetilde{MC}_t = [\tilde{r}_t - (1-\delta)]^{1-\tilde{\gamma}} / [\tilde{Z}_t \tilde{\gamma}^{\tilde{\gamma}} (1-\tilde{\gamma})^{1-\tilde{\gamma}}]. \tag{A.1}$$

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

$$\widehat{MC}_t = [\hat{r}_t - (1-\delta)]^{1-\hat{\gamma}} / [\hat{Z}_t \hat{\gamma}^{\hat{\gamma}} (1-\hat{\gamma})^{1-\hat{\gamma}}]. \tag{A.2}$$

The period t oil price markup for the dominant supplier is then

$$\mu_t \equiv \frac{P_t}{\widehat{MC}_t}. \tag{A.3}$$

In the steady-state the above expression reduces to (21), noticing that the steady-state rental price of capital, pinned down by preferences and technology, is the same across oil producers.

A.2. *Proof of Corollary 1*

In the symmetric case ($\tilde{\gamma} = \hat{\gamma}$), the average oil price markup (21) reduces to $\mu = \hat{Z}_0 / \tilde{Z}_0$. The dominant producer will thus be profitable if and only if $\hat{Z}_0 > \tilde{Z}_0$.

A.3. *Proof of Proposition 2*

Given (20)

$$\Lambda = -\frac{P\hat{O}}{\left(\frac{1}{\eta}O + \frac{\tilde{\gamma}}{1-\tilde{\gamma}}\tilde{O}\right)},$$

and given that the oil mark-up μ is $P/(P+\Lambda)$, we can solve

$$\frac{\hat{O}}{O} = \frac{\frac{\tilde{\gamma}}{1-\tilde{\gamma}} + \frac{1}{\eta}}{\frac{\tilde{\gamma}}{1-\tilde{\gamma}} - \mu} = \frac{\Phi_S + \Phi_D}{\Phi_S - \mu}.$$

A.4. *Proof of Proposition 4*

Taking the investment subsidy into account, the markup of the dominant supplier is

$$\mu = \Upsilon[g_z/\beta - (1-\delta)]^{\hat{\gamma}-\tilde{\gamma}}(1+\phi)^{1-\tilde{\gamma}}. \tag{A.4}$$

Solving this for ϕ while setting $\mu = 1$ yields expression (29).

Appendix B. The Problem of the Dominant Supplier and the Stationary Set of Equations

B.1. *The Problem of the Dominant Supplier*

The decision problem of the dominant oil producer is to maximise

$$\max_{\hat{C}_t, \hat{B}_t, \hat{X}_t, \hat{K}_t, P_t} \mathrm{E}_o \sum_{t=0}^{\infty} \beta^t \log(\hat{C}_t),$$

subject to oil demand

$$v_t C_t = P_t O_t^{\eta},$$

fringe oil supply

$$\tilde{\gamma} P_t = \frac{\tilde{O}_t^{1/\tilde{\gamma}-1}}{\tilde{Z}_t^{1/\tilde{\gamma}} \tilde{K}_{t-1}^{1/\tilde{\gamma}-1}},$$

its production technology

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

the oil market clearing condition

$$O_t = \hat{O}_t + \tilde{O}_t,$$

and its aggregate budget constraint

$$P_t \hat{O}_t = \hat{C}_t + \hat{K}_t - (1-\delta)\hat{K}_{t-1} + \hat{X}_t + \hat{B}_t - \hat{r}_{t-1}\hat{B}_{t-1}.$$

The problem can be expressed as

$$\max_{\hat{C}_t,\hat{B}_t,\hat{X}_t,\hat{K}_t,P_t} \mathrm{E}_o \sum_{t=0}^{\infty} \beta^t \left\{ \begin{array}{r} \log(\hat{C}_t) + \chi_t \left[\overbrace{\left(\frac{v_t C_t}{P_t}\right)^{\frac{1}{\eta}}}^{O_t} - \overbrace{\hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}}}^{\hat{O}_t} - \overbrace{(\tilde{\gamma} P_t \tilde{Z}_t^{1/\tilde{\gamma}})^{\frac{\tilde{\gamma}}{1-\tilde{\gamma}}} \tilde{K}_{t-1}}^{\tilde{O}_t} \right] \\ +\xi_t \left[P_t \overbrace{\hat{Z}_t \hat{X}_t^{\hat{\gamma}} \hat{K}_{t-1}^{1-\hat{\gamma}}}^{\hat{O}_t} - \hat{C}_t - \hat{K}_t + (1-\delta)\hat{K}_{t-1} - \hat{X}_t - \hat{B}_t + \hat{r}_{t-1}\hat{B}_{t-1} \right] \end{array} \right\},$$

and the first-order conditions are:

$$\frac{1}{\hat{C}_t} - \xi_t = 0,$$

$$-\xi_t + \beta \mathrm{E}_t(\xi_{t+1})\hat{r}_t = 0,$$

$$-\chi_t \hat{\gamma}\, \hat{O}_t / \hat{X}_t - \xi_t + \xi_t P_t \hat{\gamma}\, \hat{O}_t / \hat{X}_t = 0,$$

$$-\beta \mathrm{E}_t[\chi_{t+1}(1-\hat{\gamma})\, \hat{O}_{t+1}/\hat{K}_t] + \beta \mathrm{E}_t[P_{t+1}\xi_{t+1}(1-\hat{\gamma})\, \hat{O}_{t+1}/\hat{K}_t + \xi_{t+1}(1-\delta)] - \xi_t = 0,$$

$$-\chi_t \frac{1}{\eta}\frac{O_t}{P_t} - \chi_t \frac{\tilde{\gamma}}{1-\tilde{\gamma}}\frac{\tilde{O}_t}{P_t} + \xi_t \hat{O}_t = 0.$$

Defining $\Lambda_t \equiv -\chi_t/\xi_t$, we can rearrange the conditions as

$$1 = \beta \mathrm{E}_t\left(\frac{\hat{C}_t}{\hat{C}_{t+1}}\right)\hat{r}_t,$$

$$\hat{\gamma}(P_t + \Lambda_t) = \hat{X}_t / \hat{O}_t,$$

$$1 = \beta \mathrm{E}_t\left\{\frac{\hat{C}_t}{\hat{C}_{t+1}}\left[(1-\hat{\gamma})(P_{t+1}+\Lambda_{t+1})\frac{\hat{O}_{t+1}}{\hat{K}_t} + (1-\delta)\right]\right\},$$

$$\Lambda_t = -\frac{P_t \hat{O}_t}{\left(\frac{1}{\eta} O_t + \frac{\hat{\gamma}}{1-\hat{\gamma}}\tilde{O}_t\right)}.$$

B.2. *Stationary Set of Equations*

Let us define n_t as the stationary version of a non-stationary variable N_t, that is, $n_t \equiv (Z_0 N_t)/Z_t, \forall N_t \in (Y_t, K_t, C_t, I_t, \tilde{K}_t, \tilde{C}_t, \tilde{I}_t, \tilde{X}_t, \hat{K}_t, \hat{C}_t, \hat{I}_t, \hat{X}_t, B_t, \tilde{B}_t, \hat{B}_t)$. Let us also define $\tilde{o}_t \equiv \tilde{O}_t/[Z_t \exp(g^{\tilde{z}}t)]$, $\hat{o}_t \equiv \hat{O}_t/[Z_t \exp(g^{\hat{z}}t)]$, $o_t \equiv \tilde{o}_t + \hat{o}_t$, $p_t \equiv P_t \exp(g^{\tilde{z}}t)$ and $\lambda_t \equiv \Lambda_t \exp(g^{\tilde{z}}t)$ as the stationary versions of the oil-market variables $(\tilde{O}_t, \hat{O}_t, O_t, P_t, \Lambda_t)$. The complete set of stationary equations results in

Oil-importing region:

$$y_t = (Z_0 l_t)^{\alpha}(k_{t-1}\mathrm{e}^{-g_t^z})^{1-\alpha},$$
$$k_t = (1-\delta)k_{t-1}\mathrm{e}^{-g_t^z} + i_t,$$
$$v_0 c_t = p_t o_t^{\eta},$$
$$c_t l_t^{\omega} = \frac{\alpha y_t}{l_t},$$
$$1 = \beta \mathrm{E}_t\left\{\frac{c_t}{c_{t+1}\mathrm{e}^{g_{t+1}^z}}\left[\frac{(1-\alpha)y_{t+1}\mathrm{e}^{g_{t+1}^z}}{k_t} + (1-\delta)\right]\right\},$$
$$1 = \beta \mathrm{E}_t\left(\frac{c_t}{c_{t+1}\mathrm{e}^{g_{t+1}^z}}\right)r_t.$$
$$y_t = c_t + i_t + p_t o_t + b_t - r_{t-1}b_{t-1}\mathrm{e}^{-g_t^z}.$$

Competitive fringe of oil exporters:

$$\tilde{o}_t = \tilde{Z}_0 \tilde{a}_t \tilde{x}_t^{\tilde{\gamma}}(\tilde{k}_{t-1}\mathrm{e}^{-g_t^z})^{1-\tilde{\gamma}},$$
$$\tilde{k}_t = (1-\delta)\tilde{k}_{t-1}\mathrm{e}^{-g_t^z} + \tilde{i}_t,$$
$$\tilde{\gamma} p_t = \tilde{x}_t/\tilde{o}_t,$$
$$1 = \beta \mathrm{E}_t\left\{\frac{\tilde{c}_t}{\tilde{c}_{t+1}\mathrm{e}^{g_{t+1}^z}}\left[(1-\tilde{\gamma})p_{t+1}\frac{\tilde{o}_{t+1}\mathrm{e}^{g_{t+1}^z}}{\tilde{k}_t} + (1-\delta)\right]\right\},$$
$$1 = \beta \mathrm{E}_t\left(\frac{\tilde{c}_t}{\tilde{c}_{t+1}\mathrm{e}^{g_{t+1}^z}}\right)\tilde{r}_t,$$
$$p_t\tilde{o}_t = \tilde{c}_t + \tilde{i}_t + \tilde{x}_t + \tilde{b}_t - \tilde{r}_{t-1}\tilde{b}_{t-1}\mathrm{e}^{-g_t^z}.$$

Dominant supplier:

$$\hat{o}_t = \hat{Z}_0 \hat{x}_t^{\hat{\gamma}}(\hat{k}_{t-1}\mathrm{e}^{-g_t^z})^{1-\hat{\gamma}},$$
$$\hat{k}_t = (1-\delta)\hat{k}_{t-1}\mathrm{e}^{-g_t^z} + \hat{i}_t,$$
$$\hat{\gamma}(p_t + \lambda_t) = \hat{x}_t/\hat{o}_t,$$
$$1 = \beta \mathrm{E}_t\left\{\frac{\hat{c}_t}{\hat{c}_{t+1}\mathrm{e}^{g_{t+1}^z}}\left[(1-\hat{\gamma})(p_{t+1}+\lambda_{t+1})\frac{\hat{o}_{t+1}\mathrm{e}^{g_{t+1}^z}}{\hat{k}_t} + (1-\delta)\right]\right\},$$
$$1 = \beta \mathrm{E}_t\left(\frac{\hat{c}_t}{\hat{c}_{t+1}\mathrm{e}^{g_{t+1}^z}}\right)\hat{r}_t,$$
$$p_t\hat{o}_t = \hat{c}_t + \hat{i}_t + \hat{x}_t + \hat{b}_t - \hat{r}_{t-1}\hat{b}_{t-1}\mathrm{e}^{-g_t^z}.$$
$$\lambda_t = -\frac{p_t\hat{o}_t}{\left(\frac{1}{\eta}o_t + \frac{\hat{\gamma}}{1-\hat{\gamma}}\tilde{o}_t\right)}.$$

Market clearing:

$$o_t = \tilde{o}_t + \hat{o}_t,$$
$$b_t = 0,$$
$$\tilde{B}_t = 0,$$
$$\hat{b}_t = 0.$$

Bank of Spain
European Central Bank

Submitted: 3 April 2013
Accepted: 14 December 2012

References

Adelman, M. (1995). *The Genie Out of the Bottle: World Oil Since 1970*, Cambridge, MA: The MIT Press.

Alhajji, A. and Huettner, D. (2000*a*). 'OPEC and other commodity cartels: a comparison', *Energy Policy*, vol. 28 (15), pp. 1151–64.

Alhajji, A. and Huettner, D. (2000*b*). 'OPEC and world crude oil markets from 1973 to 1994: cartel, oligopoly or competitive?', *Energy Journal*, vol. 21(3), pp. 31–60.

Almoguera, P., Douglas, C. and Herrera, A. (2011). 'Testing for the cartel in OPEC: noncooperative collusion or just noncooperative?', *Oxford Review of Economic Policy*, vol. 27(4), pp. 144–68.

Al-Qahtani, A., Balistreri, E. and Dahl, C. (2008). Literature review on oil market modeling and OPEC's behavior, mimeo, Division of Economics and Business, Colorado School of Mines.

Alquist, R. and Kilian, L. (2010). 'What do we learn from the price of crude oil futures?' *Journal of Applied Econometrics*, vol. 25, pp. 539–73.

Backus, D. and Crucini, M. (2000). 'Oil prices and the terms of trade', *Journal of International Economics*, vol. 50 (1), pp. 185–213.

Baumeister, C. and Peersman, G. (2012) 'The role of time-varying price elasticities in accounting for volatility changes in the crude oil market', forthcoming: *Journal of Applied Econometrics*.

Baxter, M. and King, R.G. (1999). 'Measuring business cycles: approximate band-pass filters for economic time series', *Review of Economics and Statistics*, vol. 81(4), pp. 575–93.

Bergstrom, T.C. (1982). 'On capturing oil rents with a national excise tax', *American Economic Review*, vol. 72 (1), pp. 194–201.

Blanchard, O.J. and Gali, J. (2010). 'The macroeconomic effects of oil shocks: why are the 2000s so different from the 1970s?', in (J. Gali and M. Gertler, eds), *International Dimensions of Monetary Policy*, pp. 373–421, Chicago, IL: University of Chicago Press.

Bodenstein, M. and Guerrieri, L. (2011). 'Oil efficiency, demand and prices: a tale of ups and downs', International Finance Discussion Papers No. 1031, Board of Governors of the Federal Reserve System.

Bodenstein, M., Erceg, C.J. and Guerrieri, L. (2011). 'Oil shocks and external adjustment', *Journal of International Economics*, vol. 83(2), pp. 168–84.

Bodenstein, M., Kilian, L. and Guerrieri, L. (2011). 'Monetary policy responses to oil price fluctuations', mimeo: University of Michigan.

Brémond, V., Hache, E. and Mignon, V. (2011). 'Does OPEC still exist as a cartel? An empirical investigation', EconomiX Working Papers 2011-5.

Dahl, C. and Yucel, M. (1991). 'Testing alternative hypotheses of oil producer behavior', *Energy Journal*, vol. 12(4), pp. 117–38.

De Miguel, C. and Manzano, B. (2006). 'Optimal oil taxation in a small open economy', *Review of Economic Dynamics*, vol. 9(3), pp. 438–54.

Edelstein, P., and Kilian, L. (2009). 'How sensitive are consumer expenditures to retail energy prices?' *Journal of Monetary Economics*, vol. 56(6), pp. 766–79.

Farzin, Y.H. (1992). 'The time path of scarcity rent in the theory of exhaustible resources', ECONOMIC JOURNAL, vol. 102(413), pp. 813–30.

Goulder, L. (1994). 'Energy taxes: traditional efficiency effects and environmental implications', in (J.M. Poterba, eds.), *Tax Policy and the Economy*, vol. 8, pp. 105–58, Cambridge, MA: MIT Press.

Hamilton, J.D. (2009). 'Understanding crude oil prices', *Energy Journal*, vol. 30(2), pp. 179–206.

Hassler, J., Krusell, P. and Olovsson, C. (2010). 'Oil monopoly and the climate', *American Economic Review, Papers and Proceedings*, vol. 100(2), pp. 460–4.

International Energy Agency (2008). *World Energy Outlook 2008*, Paris: OECD.

International Energy Agency (2009). *World Energy Outlook 2009*, Paris: OECD.

Karp, L. and Newbery, D.M. (1991). 'OPEC and the U.S. oil import tariff', ECONOMIC JOURNAL, vol. 101(405), pp. 303–13.

Kilian, L. (2008*a*). 'The economic effects of energy price shocks', *Journal of Economic Literature*, vol. 46(4), pp. 871–909.

Kilian, L. (2008*b*). 'Exogenous oil supply shocks: how big are they and how much do they matter for the US economy?', *Review of Economics and Statistics*, vol. 90(2), pp. 216–40.

Kilian, L. (2009). 'Not all oil price shocks are alike: disentangling demand and supply shocks in the crude oil market', *American Economic Review*, vol. 99(3), pp. 1053–69.
Kilian, L. and Murphy, D.P. (2010). 'The role of inventories and speculative trading in the global market for crude oil', mimeo, University of Michigan.
Kilian, L. and Park, C. (2009). 'The impact of oil price shocks on the US stock market', *International Economic Review*, vol. 50(4), pp. 1267–287.
Leduc, S. and Sill, K. (2007). 'Monetary policy, oil shocks, and TFP: accounting for the decline in US volatility', *Review of Economic Dynamics*, vol. 10(4), pp. 595–614.
Lee, K. and Ni, S. (2002). 'On the dynamic effects of oil price shocks: a study using industry level data', *Journal of Monetary Economics*, vol. 49(4), pp. 823–52.
Litzenberger, R. H. and Rabinowitz, N. (1995). 'Backwardation in oil futures markets: theory and empirical evidence', *Journal of Finance*, vol. 50(5), pp. 1517–45.
Mabro, R. (1975). 'Can OPEC hold the line?', in *OPEC and the World Oil Market: The Genesis of the 1986 Price Crisis*, Oxford: Oxford Institute for Energy Studies.
Maskin, E.S. and Newbery D.M. (1990). 'Disadvantageous oil tariffs and dynamic consistency', *American Economic Review*, vol. 80(1), pp. 143–56.
Milani, F. (2009). 'Expectations, learning, and the changing relationship between oil prices and the macroeconomy', *Energy Economics*, vol. 31(6), pp. 827–37.
Nakov, A. and Pescatori, A. (2010*a*). 'Monetary policy tradeoffs with a dominant oil producer', *Journal of Money, Credit and Banking*, vol. 42(1), pp. 1–32.
Nakov, A. and Pescatori, A. (2010*b*). 'Oil and the great moderation', Economic Journal, vol. 120(543), pp. 131–56.
Rotemberg, J.I. and Woodford, M. (1994). 'Energy taxes and aggregate economic activity', *NBER Chapters*, vol. 8, pp. 159–95.
Salant, S. W. (1976). 'Exhaustible resources and industrial structure: a Nash–Cournot approach to the world oil market', *Journal of Political Economy*, vol. 84(5), pp. 1079–94.
Smith, J. (2005). 'Inscrutable OPEC? Behavioral tests of the cartel hypothesis', *Energy Journal*, vol. 26(1), pp. 51–82.
Smith, J. (2009). 'World oil: market or mayhem?', *Journal of Economic Perspectives*, vol. 23(3), pp. 145–64.
Ulph, A.M. and Folie, G.M. (1981). 'Dominant firm models of resource depletion', in (ed. D. Currie, D. Peel and W. Peters, eds), *Microeconomic Analysis*, pp. 77–106, London: Croom Helm.
Yergin, D. (1992). *The Prize: The Epic Quest for Oil, Money & Power*, New York: Free Press.