An Empirical Dynamic Model of OPEC and Non-OPEC

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Abstract

This paper estimates a dynamic model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved oligopolistically over the period 1970-2004. The model generates estimates of the shadow price of the resource with minimal functional form assumptions. Results support oligopolistic behavior among non-OPEC producers and collusion among OPEC producers except in the last 15 years. The shadow price does not rise monotonically, which is evidence for stock effects in extraction costs. The recent rise in the shadow price reflects the rising economic scarcity of oil.

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1 Introduction

Oil is one of the most important resources on the planet today. Oil is a form of power, not only because it is a primary source of the energy needed to power modern industrialized society (Yergin, 1992), but also because its possession itself is a source of power. Oil not only fuels our cars, heats our homes and runs our factories, but also drives national economic, political and military policy around the world.

Because oil is such a valuable resource, analyses of the petroleum market are important to academics, businesspeople and policy-makers alike. In particular, OPEC and OPEC strategy have long fascinated and puzzled economists. It is clear that OPEC producers behave strategically and that OPEC wields much power over the world oil market. But what exactly is OPEC's strategy, and is it possible to model it?

As a step towards better understanding and modeling the world oil market and OPEC in particular, this paper estimates a dynamic model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved as price takers or oligopolists over the period 1970-2004. The model generates estimates of the shadow price of the resource with minimal functional form assumptions.

The research in this paper makes several important contributions to the existing literature. First, it takes to data the theoretical model of optimal nonrenewable resource extraction that was first examined by Hotelling (1931), and later expanded upon by many others to allow for such features such as Nash-Cournot behavior (Salant, 1976; Ulph & Folie, 1980), OPEC (Hnyilicza & Pindyck, 1976; Pindyck, 1976; Cremer & Weitzman, 1976), stock effects in extraction costs (Farzin, 1992; Hanson, 1980; Solow & Wan, 1976), exploration (Pesaran, 1990; Pindyck, 1978), market imperfections (see Cremer & Salehi-Isfahani, 1991 and references therein; Khalatbari, 1977; Stiglitz, 1976; Sweeney, 1977), technological progress (Farzin, 1992, 1995; Lin et al., 2007; Lin & Wagner, 2007), outward-shifting demand (Chapman, 1993; Chapman &

Khanna, 2000), and uncertainty (Hoel, 1978; Pindyck, 1980).[2] Thus, unlike many previous studies of the petroleum market, this paper estimates a dynamic model of the world petroleum market.

The second contribution is that this paper builds upon existing empirical studies of the petroleum market (see e.g., Adelman, 1962; Berndt & Wood, 1975; Gately, 1984; Gately & Huntington, 2002; Griffin, 1985; Hausman, 1975; Kennedy, 1974; Nordhaus, 1980) by addressing the identification problem that arises in empirical analyses of supply and demand. Because the observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, instrumental variables are needed to address the endogeneity problem (Angrist et al., 2000; Goldberger, 1991; Lin, 2006; Manski, 1995).

The third contribution is that this paper develops a dynamic model with minimal functional form assumptions that enables one to test for the market conduct of OPEC and non-OPEC producers. This paper builds upon the work of Griffin (1985), who tests alternative models of OPEC behavior using quarterly data over the period 1971-1983, by using a dynamic model, by using instrumental variables to address endogeneity, and by incorporating two additional decades of recent data. It expands upon the work of Matutes (1988) by using instruments and by incorporating more recent data. This paper also builds upon the literature on conduct parameter analysis (see e.g., Genesove & Mullin, 1998; Corts, 1999 & references therein) by estimating a dynamic model. Farzin (1985) estimates a supply function for non-OPEC producers using U.S. data from 1973-1978; this paper considers the supply function for both OPEC and non-OPEC producers over a longer period of time.[3]

The fourth contribution of this paper is that it estimates the shadow price of the resource. Since the shadow price of scarcity reflects the scarcity of oil and is an indicator of sustainability, the measurement of the shadow price has been the subject of much interest and previous work

[2] For a comprehensive survey of models of the oil market, see Cremer and Salehi-Isfahani (1991).

[3] The dynamics in this paper arise from the nonrenewable nature of the resource. The empirical method presented in this paper also yields efficient estimates of the conduct parameter when there is efficient tacit collusion resulting from dynamic cartel behavior, as in Puller (2006), but the shadow price would no longer be separately identified.

(Hartwick & Olewiler, 1998), including that by, among others, Devarajan and Fisher (1982), Halvorsen and Smith (1984, 1991), and Lasserre (1985). For example, Halvorsen and Smith (1984, 1991) use a restricted cost function to estimate the shadow price for the Canadian metal mining industry over the period 1954-1974. Several authors have proposed that the shadow price is the best single index of trends in resource scarcity (see e.g., Brown & Field, 1978; Fisher, 1981). This paper presents a method for obtaining an estimate of the shadow price of oil over 1970-2004 with minimal functional form assumptions.

Results support oligopolistic behavior among non-OPEC producers and collusion among OPEC producers except in the last 15 years. The shadow price does not rise monotonically, which is evidence for stock effects in extraction costs.

The balance of this paper proceeds as follows. Section 2 presents the theoretical Hotelling model of nonrenewable resource extraction under the market structures of perfect competition, Cournot oligopoly and monopoly (or collusion). Section 3 presents the empirical estimation. Section 4 concludes.

2 The Theoretical Model of Nonrenewable Resource Extraction

Let t index time. At time t, each producer j supplies $q_j(t)$ of the nonrenewable resource. The total quantity supplied at time t is given by $Q(t) = \sum_j q_j(t)$. The market price of oil at time t is $P(t)$. The corresponding demand is given by $D(P(t))$. At each time t, the market price $P(t)$ adjusts to equate supply and demand:

$$Q(t) = D(P(t)) \; \forall t. \tag{1}$$

.

$C(S, Q, t)$ depicts the cost of extracting Q tons at time t when the stock of oil remaining in the ground is S. Costs may depend on time if, for example, there is technological progress. Solow and Wan (1976) as well as Swierzbinski and Mendelsohn (1989) discuss procedures for aggregating across multiple deposits of an exhaustible resource with different extraction costs.

The term "stock effects" refers to the dependence of extraction cost on the stock S of reserve remaining in the ground. There are several possible reasons why this dependence is negative. First, extraction costs may increase as more of the stock is extracted (and less remains in the ground) if the resource needed to be extracted from greater depths as it was being depleted. Second, costs may increase if well pressure declined as more of the reserve was depleted. Third, since different grades of oil may differ in their extraction costs, and since the cheaper grades are likely to be mined to exhaustion before the more expensive grades are mined, the cost of extraction may increase as the cheaper grades are exhausted.

Let $p(t)$ denote the non-negative current-value shadow price measuring the value of a ton of reserve *in situ* at time t. This shadow price is known by a variety of terms, including marginal user cost, *in situ* value, scarcity rent, dynamic rent, and resource rent (Devarajan & Fisher, 1982; Krautkraemer, 1998; Weitzman, 2003). The competitive interest rate is r.

The producer's optimal nonrenewable resource extraction problem is to choose the extraction profile $\{Q(t)\}$ to maximize the present discounted value of the entire stream of per-period net benefits $G(S, Q, t)$, given initial stock S_o and the relationship between extraction $Q(t)$ and stock remaining $S(t)$, and subject to the constraints that both extraction and stock are nonnegative. Her problem is thus given by:

$$
\begin{aligned}
&\max_{\{Q(t)\}} \int_0^\infty \left(G(S(t), Q(t), t)\right) e^{-rt} dt \\
&\text{s.t.} \qquad \dot{S}(t) = -Q(t) \qquad : p(t) \\
&\qquad\qquad Q(t) \geq 0 \\
&\qquad\qquad S(t) \geq 0 \\
&\qquad\qquad S(0) = S_0 \quad ,
\end{aligned}
\tag{2}
$$

where the co-state variable $p(t)$ associated with the remaining stock $S(t)$ is the shadow price $p(t)$ of the reserve still in the ground, measuring the marginal value in terms of present discounted net benefits that could be obtained with an extra unit of reserve.

Under perfect competition, the per-period net benefits $G(S,Q,t)$ from extracting Q tons at time t are given by total benefits $U(Q,t)$ minus total costs:

$$G(S,Q,t) = U(Q,t) - C(S,Q,t). \tag{3}$$

Assuming that the social and private discount rates are the same, that the initial stock S_0 is known, and that there are no externalities, the social planner's optimal control problem yields the same solution as would arise in perfect competition. In this case, under the additional assumption that the marginal utility of income is constant, the total benefits $U(\cdot,\cdot)$ that accrue from the consumption of the mineral at time t are given by the area under the demand curve,

$$U(Q(t),t) = \int_0^{Q(t)} D^{-1}(x;t)dx, \tag{4}$$

where $D^{-1}(\cdot;t)$ is the inverse of the demand curve with respect to price. This area measures the gross consumer surplus, and is a measure of the consumers' willingness-to-pay for the resource. Weitzman (2003) shows that using the area under the demand curve in place of revenue yields the same outcome as a perfectly competitive market.[4] Thus, in the absence of externalities, a perfectly competitive market maximizes total utility, or what Hotelling (1931) terms the "social value of the resource".

When oil is produced by a single monopolist or by a group of colluding joint profit maximizing producers, rather than by a multitude of perfectly competitive producers, the per-period net

[4] This holds because, assuming constant marginal utility of income:

$$P(t) = \frac{\partial U(Q(t))}{\partial Q},$$

so that the first-order conditions for the social planner's problem are the same as those that arise in perfect competition.

benefits $G(S,Q,t)$ are given by the monopolist's per-period profit, which equals total revenue minus total costs. Total revenue $R_m(\cdot)$ at time t is given by:

$$R_m(Q(t)) = D^{-1}(Q(t)) \cdot Q(t). \tag{5}$$

As a consequence, the monopolist's per-period profit $G(S,Q,t)$ is given by:

$$G(S,Q,t) = R_m(Q) - C(S,Q,t). \tag{6}$$

The revenue $R_j(\cdot)$ for each producer j is given by:

$$R_j(q_j(t)) = D^{-1}(Q(t)) \cdot q_j(t). \tag{7}$$

Thus, under Cournot oligopoly, the per-period profits $G_j(S,q_j,t)$ for each producer j is j's revenue $R_j(q_j)$ minus its costs $C_j(S,q_j,t)$:

$$G(S,q_j,t) = R_j(q_j) - C_j(S,q_j,t). \tag{8}$$

From the Maximum Principle, one first-order necessary condition for a feasible trajectory $\{S^*(t), Q^*(t)\}$ to be optimal under perfect competition is:

$$[\#1 \text{ perfect competition}]: \qquad P(t) = \frac{\partial C(\cdot)}{\partial Q} + p(t). \tag{9}$$

Under collusion, this first-order condition is:

$$[\#1 \text{ collusion}]: P(t) = -\frac{\partial D^{-1}(Q(t))}{\partial Q} Q(t) + \frac{\partial C(\cdot)}{\partial Q} + p(t). \tag{10}$$

Under Cournot oligopoly, this first-order condition is:[5]

$$[\#1 \text{ Cournot}]: P(t) = -\frac{\partial D^{-1}(Q(t))}{\partial Q} q_j(t) + \frac{\partial C_j(\cdot)}{\partial q_j} + p(t). \tag{11}$$

A second first-order condition governs the time rate of change of the shadow price:[6]

$$[\#2]: \qquad \dot{p}(t) = \frac{\partial C(\cdot)}{\partial S} + rp(t), \tag{12}$$

which, in the absence of stock effects ($\frac{\partial C}{\partial S}(\cdot) = 0$), yields the Hotelling rule that the shadow price rises at the rate of interest:

$$p(t) = p(0)e^{rt}. \tag{13}$$

[5] In the Stackelberg model with the OPEC producers jointly acting as the Stackelberg leader, the first first-order condition for the OPEC leader would be given by:

$$[\#1 \text{ Stackelberg leader}]: P(t) = -\frac{\partial D^{-1}(Q(t))}{\partial Q}\left(1 + \frac{\partial r_2(Q_{OPEC}(t))}{\partial Q_{OPEC}}\right) Q_{OPEC}(t) + \frac{\partial C_j(\cdot)}{\partial q_j} + p(t),$$

where Q_{OPEC} is the total OPEC quantity and $r_2(Q_{OPEC})$ is the reaction function for the non-OPEC followers given by the solution to either the perfect competition first-order condition (9) or the Cournot first-order condition (11), with $Q = Q_{OPEC} + \sum_{j \notin OPEC} q_j$. Without additional function form assumptions, however, one cannot separately identify the slope of the reaction function in a regression of price on quantity and marginal cost, and thus cannot distinguish between simultaneous-move and Stackelberg behavior between OPEC and non-OPEC in the empirical analysis. The market power tests developed in this paper are robust to whether OPEC producers move first or at the same time as non-OPEC producers and do not require these possibly restrictive and potentially unrealistic functional form assumptions.

[6] The third first-order condition is the transversality condition:

$$[\#3]: \qquad \lim_{t \to \infty} p(t)S(t)e^{-rt} = 0$$

3 Empirical Estimation

The empirical model allows for the possibility that OPEC producers either colludes or not and that non-OPEC producers behave either as Cournot oligopolists or as perfectly competitive price-takers.[7] The general supply-side first-order condition is:

$$P(t) = -\theta_1 \frac{\partial D^{-1}(Q(t))}{\partial Q} q_j(t) \cdot \left(1 - I_j^{OPEC}\right) - \theta_2 \frac{\partial D^{-1}(Q(t))}{\partial Q} Q^{OPEC}(t) \cdot I_j^{OPEC} + \frac{\partial C_j\left(\cdot\right)}{\partial q_j} + p(t), \tag{14}$$

where I_j^{OPEC} is an indicator variable that equals 1 if producer j is an OPEC producer and $Q^{OPEC}(t)$ is the total OPEC quantity at time t. If $\theta_1 = 0$, then the non-OPEC producers are perfectly competitive price takers; if $\theta_1 = 1$, then the non-OPEC producers are Cournot oligopolists. If $\theta_1 \in (0,1)$, this means that the non-OPEC producers exert an intermediate degree of market power. OPEC producers are perfectly colluding if $\theta_2 = 1$, but are not colluding if $\theta_2 = 0$. If $\theta_2 \in (0,1)$, then the OPEC producers are colluding, but imperfectly.[8]

I use country-level data on extraction, price and cost for oil over the period 1970 to 2004 from previously unpublished World Bank data.[9] Table 1 presents summary statistics. I assume that extraction costs exhibit constant returns to scale with respect to extraction, and therefore that marginal costs equal average costs. For my specifications with a flexible shadow price that allows for the possibility of stock effects, this is the only functional form assumption that I make in this paper. This assumption is justified for several reasons. First, constant returns to scale in the extraction of nonrenewable resources is a common assumption. It is often posited that the extraction cost function exhibits constant returns to scale, where the marginal

[7] Modeling selection into OPEC will be the subject of future work.

[8] I focus on the cases where non-OPEC producers are either price-takers or oligopolists, and where OPEC producers are either colluding or not, as these are the market structure scenarios most commonly considered in the literature and most likely to reflect the reality of the petroleum market. Results of models that allowed for other possible market structures such as collusion among non-OPEC producers (not shown) yielded unrealistic parameter values such as a negative shadow price, which corroborates this view.

[9] I thank Kirk Hamilton for providing the data. The World Bank data include average "rent" figures, which were calculated as extraction times the difference between price and average cost; I use this formula to calculate average costs.

extraction cost is increasing in cumulative extraction but independent of the current rate of extraction, and therefore that average cost and marginal cost are the same (see e.g., Hanson, 1980; Lin & Wagner, 2007; Solow & Wan, 1976). Second, the assumption of constant returns to scale enables one to define an aggregate extraction cost function that aggregates across multiple deposits of an exhaustible resource with different extraction costs. Solow and Wan (1976) and Swierzbinski and Mendelsohn (1989) show that in the absence of exploration, if firms extract first from the cheapest deposits and there are constant returns to scale in extraction, then an aggregate extraction cost function can be defined and indexed by the amount of cumulative extraction.

To estimate equation (14), I run a two-stage least squares regression of world price on quantity for non-OPEC producers, total OPEC quantity for OPEC producers and average cost. Quantity in non-OPEC countries is instrumented with country population. Total OPEC quantity is instrumented with world population. Table 2 presents the results from the first-stage regressions. The coefficient on country population is statistically significant in the first-stage regression on quantity in non-OPEC countries and the coefficient on world population is statistically significant in the first-stage regression of total OPEC quantity.[10]

I incorporate the shadow price into the regression in two ways. The first way is to include as a regressor e^{rt}, so that the coefficient on this regressor is the initial shadow price in 1970 under the assumption that there are no stock effects. I set $r = 5\%$. The second way, which allows for the possibility of stock effects and thus imposes no additional assumptions on the cost function, is to estimate year effects; the value of each year effect is the value of the shadow price during that year.[11] In order to allow for the possibility that market structure and demand

[10] In the first-stage regression of total OPEC quantity, world population is collinear with the year effects when the sample is limited to OPEC countries only. However, this instrument is no longer collinear in the model, which uses all the countries.

[11] Corts (1999) shows that the conduct parameter can be inconsistently estimated if producers are engaging in efficient tacit collusion. Puller (2006) shows that in the first-order condition the extra term that results from a binding incentive compatibility constraint can be conditioned out using time fixed effects, yielding consistent estimates of the conduct parameter. If the producers are engaging in tacit collusion, then the inclusion of time fixed effects in this specification leads to consistent estimates of the conduct parameter, but the shadow price would no longer be separately identified.

elasticities may have changed over the period 1970-2004, I also run the model allowing the conduct parameters θ_1 and θ_2 to vary by decade.

If the coefficient on quantity produced for non-OPEC producers is statistically significant, then, assuming that the slope of the inverse demand curve is non-zero, this means that $\theta_1 > 0$ and therefore that the non-OPEC producers exhibit market power as (possibly imperfect) Cournot oligopolists; otherwise, $\theta_1 = 0$ and they behave as price-takers. Similarly, if the coefficient on total OPEC quantity for OPEC producers is statistically significant, then, assuming that the slope of the inverse demand curve is non-zero, this means that $\theta_2 > 0$ and the OPEC producers are colluding, possibly imperfectly; otherwise, $\theta_1 = 0$ and they are not colluding. Since demand is downward-sloping, we expect the coefficients on quantity for non-OPEC producers and total OPEC quantity for OPEC producers to be positive when $\theta_1 > 0$ and $\theta_2 > 0$, respectively. The assumption that demand is downward-sloping and therefore that it is not perfectly inelastic is supported by empirical studies, which estimate the price elasticity of demand for oil to be in the range -0.5 to -0.1 (see e.g., Berndt & Wood, 1975, p. 265; Dahl, 1993, 1994a,b; Edmonson, 1975, p. 172; Nordhaus, 1980, p. 347; Pindyck, 1978, p. 857).

Table 3 presents the results from estimating the model. In both specification (1), when the shadow price is assumed to rise at the rate of interest, and specification (2), which allows for a flexible shadow price, the coefficients on both quantity for non-OPEC producers and total OPEC quantity for OPEC producers statistically significant, which means that the non-OPEC producers behaved oligopolistically and the OPEC producers colluded. Moreover, the coefficients are positive, which is consistent with a downward-sloping demand function.

Specifications (3) and (4) allow the conduct parameters and elasticities to vary by decade. Specification (4), which has a flexible shadow price that allows for the possibility of stock effects, appears to better explain the data than does specification (3), which yields a positively sloping demand curve faced by non-OPEC countries in the 1990s. Both models show that non-OPEC producers behaved oligopolistically and OPEC producers colluded in the earlier half of the time period, but that we cannot reject perfect competition in the oil market in the latter half of the time period.

In all specifications, as expected, average costs has a significantly positive effect on oil price and the shadow price is significantly positive.

The coefficient on quantity in non-OPEC producers is $-\theta_1 \frac{\partial D^{-1}(Q(t))}{\partial Q}$, which is a product of the market conduct parameter θ_1 and the (absolute value of the) slope of the inverse demand curve. Similarly, the coefficient on OPEC quantity is $-\theta_2 \frac{\partial D^{-1}(Q(t))}{\partial Q}$, which is a product of the market conduct parameter θ_2 and the (absolute value of the) slope of the inverse demand curve. If $\theta_1 = \theta_2 = 1$, then the coefficients should be equal to each other and should yield the (absolute value of the) slope of the inverse demand curve. In periods when the oil market is not perfectly competitive, the test of the null hypothesis that the coefficients on quantity for the OPEC and non-OPEC producers are equal to each other can be rejected at a 5% level, which suggests that despite the presence of market power, either the degree of market power exerted by the non-OPEC producers was imperfect or the degree of collusion among the OPEC producers was imperfect, or both.[12]

One strength of the analysis presented in this paper is that it enables one to test market power and estimate the shadow price with minimal functional form assumptions. Moreover, because supply is identified, a model of demand is not needed. Like oil supply, oil demand is very difficult to model accurately and beyond the scope of this present analysis. The results of this paper therefore do not depend on any particular functional form assumption or estimation of demand. Coupling this paper's supply-side model with a demand-side model to estimate the demand elasticity and the conduct parameters will be the subject of future work.

Figures 1 and 2 plot the estimated shadow price trajectory under specifications (2) and (4), respectively. The dotted lines denote the 95% confidence interval. The dotted lines closely

[12] The coefficients on quantity enable one to obtain an upper bound to the magnitude of the demand elasticity. Evaluated at mean price and quantity, the upper bound for the absolute value of the point estimate for the demand elasticity when perfect competition can be rejected ranges from 4.14 to 910.32 in the specifications that allowed conduct parameters and elasticities to vary by decade. Because they are upper bounds, these values are much more elastic than the elasticity estimates seen in the previous literature (see e.g., Berndt & Wood, 1975; Dahl 1993, 1994a,b; Edmonson, 1974; Nordhaus, 1980; Pindyck, 1978), and thus provide further evidence for intermediate forms of market power and collusion: i.e., $\theta_1 \in (0, 1)$ and $\theta_2 \in (0, 1)$ rather than $\theta_1 = 1$ and $\theta_2 = 1$.

track the point estimate: the standard errors are small, and thus the confidence interval is very small. The shadow price appears robust to whether the market conduct was allowed to vary by decade, and is precisely estimated in both specifications. It follows an inverse U-shaped pattern until around 1997, with the peak in the year 1980 at a real price of approximately \$327/ton (or approximately \$44.79/barrel),[13] and has begun to rise again starting in the late 1990s. The recent rise in the shadow price reflects the rising economic scarcity of oil.

4 Conclusion

This paper estimates a dynamic model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved as price takers or oligopolists over the period 1970-2004. The model generates estimates of the shadow price of the resource with minimal functional form assumptions.

When the data is pooled over entire time period, results support oligopolistic behavior among non-OPEC producers and collusion among OPEC producers. When separated by decade, however, results do not support either oligopoly among non-OPEC producers or collusion among OPEC producers in the production of oil in the last 15 years. Oligopolistic behavior among non-OPEC producers in the beginning of the period is consistent with Roncaglia (1985), whose study of the international oil market from its inception to the early 1980s characterized the market as that of trilateral oligopoly.[14] Collusion among OPEC producers in the earlier period is consistent with the results of Griffin (1985), who finds that over 1971-1983, the partial market-sharing cartel model could not be rejected for all 11 countries.

The result that OPEC producers have not succeeded in colluding in recent years is consistent with the studies of Marcel and Mitchell (2006) and Sperling and Gordon (2007), who argue that while OPEC producers may have succeeded in colluding when OPEC was first formed,

[13] Assuming a specific gravity of 33 API, one ton of crude oil is equivalent to approximately 7.3 barrels of crude oil (http://www.eppo.go.th/ref/UNIT-OIL.html).

[14] In his testing among cartel, competitive, target revenue, and property rights models, Griffin (1985) finds that over 1971-1983 the competitive model could not be rejected for 10 of 11 non-OPEC producers. His result is not inconsistent with the result of this paper, however, because oligopoly was not one of the models considered.

they have failed to behave as a cartel in the past two decades in part because the state-owned companies that comprise OPEC have juggled multiple objectives, economic and otherwise, and thus have not acted so as to maximize joint profits. According to a Baker Institute study, noncommercial objectives of national oil companies, which have interfered with the firms' ability to produce at a technically efficient level and to maximize overall value, include oil wealth redistribution to society at large; foreign and strategic policy and alliance building; energy security; and participation in national-level politics (Baker Institute, 2007). The results on OPEC collusion and non-collusion are also consistent with those of Lin (2007), who finds in her simulations of the basic Hotelling model that a monopolistic market structure better explains the world oil market than perfect competition does prior to the 1973 Arab oil embargo, but that perfect competition fares better in the years following it.

The dynamic model also generates precise estimates of the shadow price for oil. The shadow price does not rise monotonically, which is evidence for stock effects in extraction costs. The recent rise in the shadow price reflects the rising economic scarcity of oil, possibly reflecting a combination of increasing geologic scarcity and a diminishing marginal return on technological progress (in terms of decreasing marginal extraction cost). While technological progress may have offset the rising geologic scarcity of oil in the past, this may no longer be the case. Even if there still exists an ample supply of unconventional sources of oil, we may eventually reach the point where these marginal reserves are no longer economic to extract.

Both the result that, particularly in recent years, national oil companies, which controlled 77 percent of the total global proven reserves in 2005 (Baker Institute, 2007), are difficult to model and understand, and the result that oil is becoming economically scarce, point to an important policy implication. In order to wean society from its dependence on an increasingly scarce resource that is controlled by potentially volatile and unreliable producers, policy-makers should provide incentives for research, development and investment in energy efficiency and alternative sources of energy.

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TABLE 1. Summary statistics

Variable	**# obs**	**mean**	**s.d.**	**min**	**max**
oil price (1982-1984 US $ per ton)	2659	130.03	68.94	33.49	327.74
oil quantity extracted (million tons)	2659	35.71	78.57	0.0007	569.48
average cost of extraction (1982-1984 US $ per ton)	2659	31.17	21.21	3.18	103.87
country population (million)	2659	55.25	156.05	0.11	1296.16
world population (million)	35	5011.82	820.08	3678.38	6363.20

Notes: The data consists of annual country-level data over the period 1970-2004. There are 103 countries producing oil.
Source: Unpublished World Bank data.

TABLE 2. First-stage regressions

	Dependent variable is quantity of oil (million tons)		
	for non-OPEC countries (1)	for non-OPEC countries (2)	total OPEC quantity for OPEC countries (3)
country population (million) * is not an OPEC country	0.13 ***	0.13 ***	
	(0.01)	(0.01)	
world population (million) * is an OPEC country			0.34 ***
			(0.01)
average cost of extraction (1982-1984 US $ per ton)	0.38 ***	0.45 ***	1.89
	(0.05)	(0.06)	(0.88)
e^{rt}	1.20		-184.05 ***
	(0.65)		(15.33)
year effects	N	Y	N
# observations	2244	2244	415

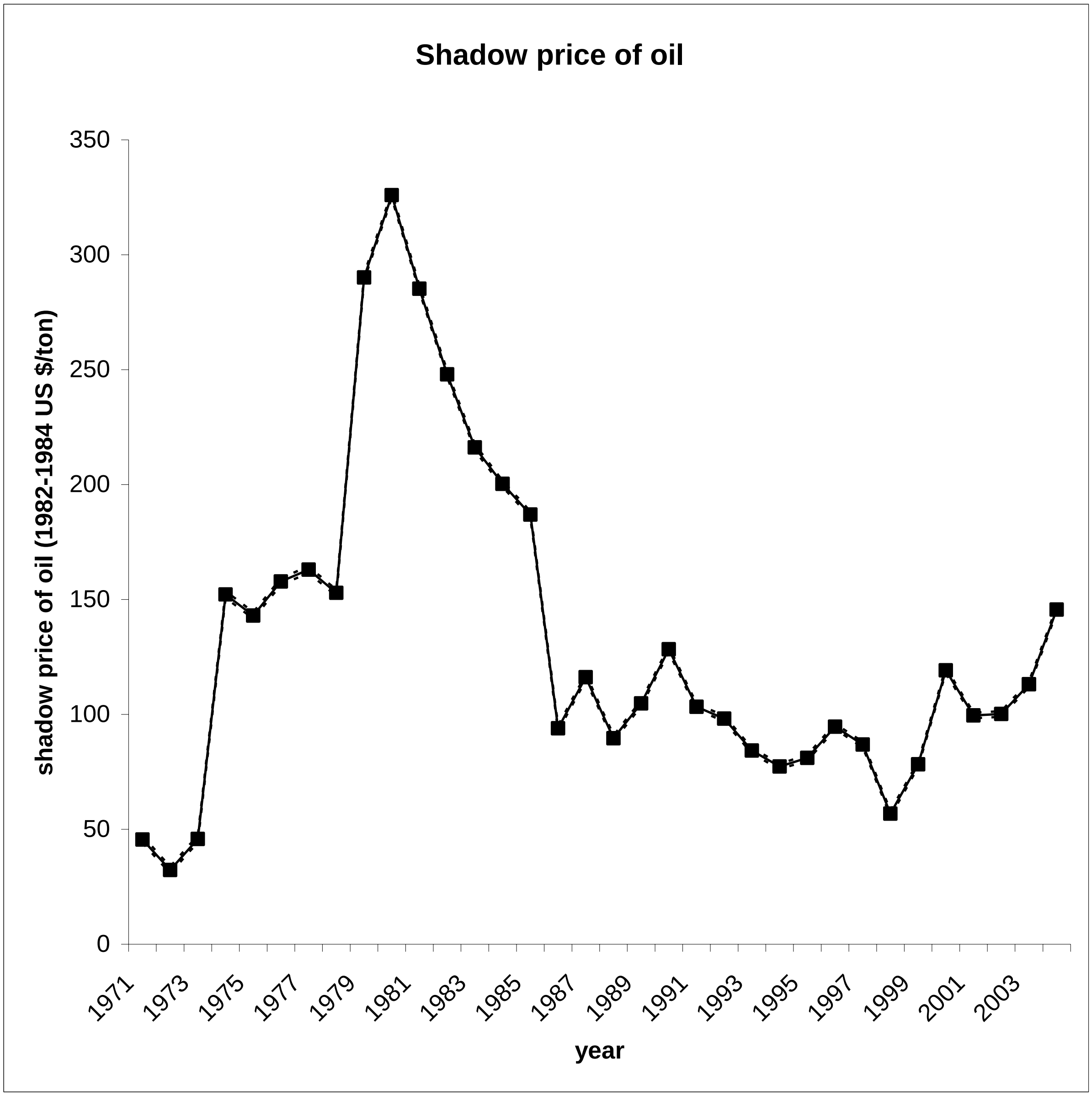
Notes: Standard errors in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

TABLE 3. Results of dynamic model

Dependent variable is real price of oil (1982-1984 US $ per ton)				
	(1)	(2)	(3)	(4)
quantity (million tons) * is not an OPEC country	0.39 ***	0.015 **		
	(0.09)	(0.005)		
1970-1979			0.88 ***	0.08 ***
			(0.19)	(0.01)
1980-1989			1.09 ***	0.00
			(0.13)	(0.01)
1990-1999			-0.26	0.00
			(0.13)	(0.01)
2000-2004			-0.26	0.00
			(0.18)	(0.01)
OPEC quantity (million tons) * is an OPEC country	0.05 ***	0.001 ***		
	(0.00)	(0.000)		
1970-1979			0.05 ***	0.004 ***
			(0.01)	(0.000)
1980-1989			0.11 ***	0.00
			(0.01)	(0.00)
1990-1999			-0.00	0.00
			(0.01)	(0.00)
2000-2004			-0.00	0.00
			(0.01)	(0.00)
average cost of extraction (1982-1984 US $ per ton)	1.77 ***	0.04 ***	1.47 ***	0.04 ***
	(0.08)	(0.01)	(0.08)	(0.01)
e^{rt}	14.37 ***		19.74 ***	
	(0.88)		(1.07)	
year effects	N	Y	N	Y
# observations	2659	2659	2659	2659
Result of test that coefficient on total OPEC quantity for OPEC producers is equal to the coefficient on quantity for non-OPEC producers				
p-value	[0.00] ***	[0.01] *		
1970-1979			[0.00] ***	[0.00] ***
1980-1989			[0.00] ***	[0.86]
1990-1999			[0.05]	[0.94]
2000-2004			[0.16]	[0.96]

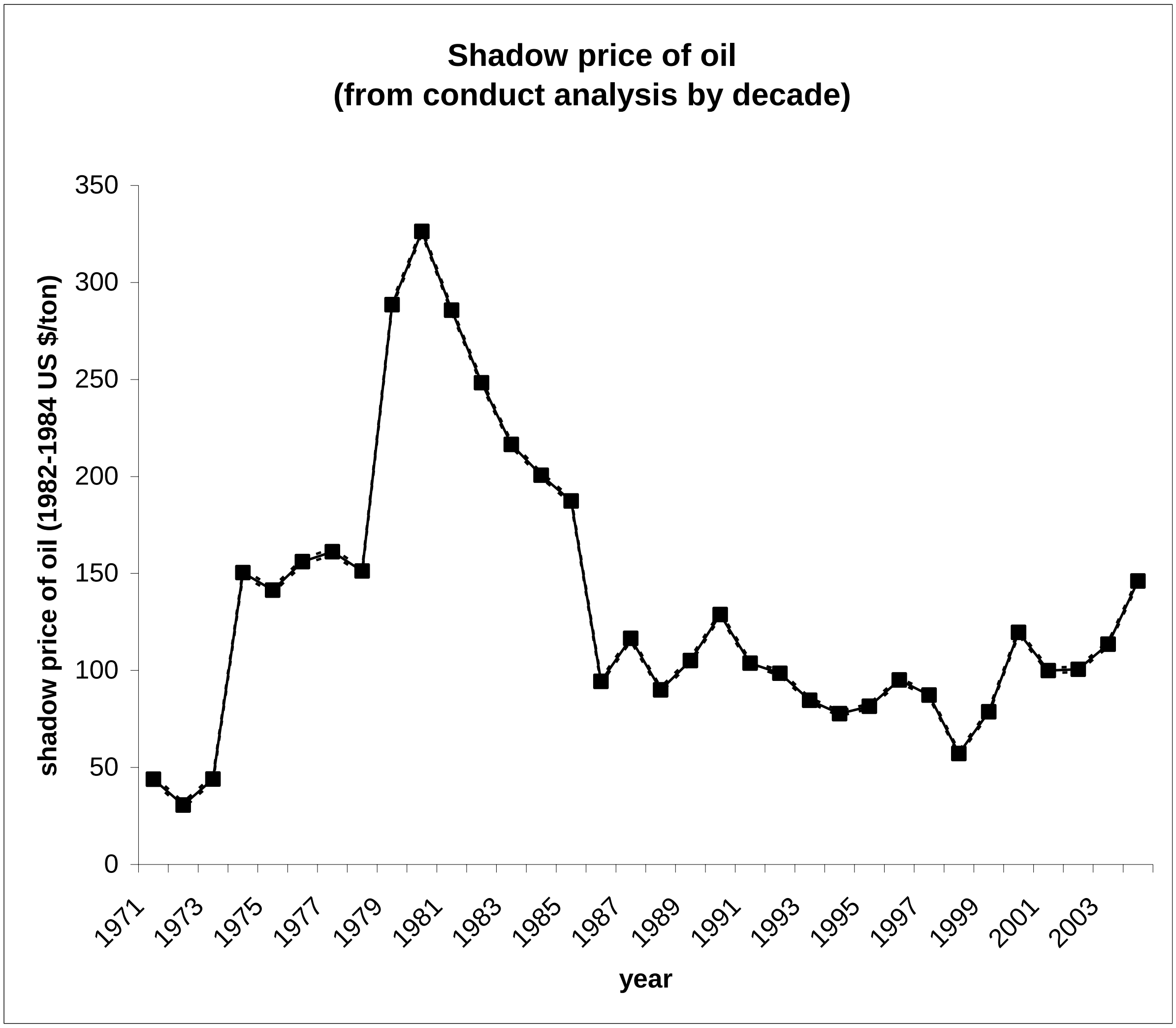
Notes: Standard errors in parentheses. In regressions without year effects, the coefficient on e^{rt} is the initial shadow price at year 1970. In regressions with year effects, the year effects represent the value of the shadow price. Quantity in non-OPEC countries is instrumented with country population. Total OPEC quantity is instrumented with world population.
Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

FIGURE 1.



Note: These estimates are generated from specification (2) in Table 3. Dotted lines (which track the solid line closely) denote the 95% confidence interval.

FIGURE 2.



Note: These estimates are generated from specification (4) in Table 3. Dotted lines (which track the solid line closely) denote the 95% confidence interval.