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OPEC's market power: An Empirical Dominant Firm Model for the Oil Market[*]

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Abstract

In this paper we estimate a dominant firm–competitive fringe model for the crude oil market using quarterly data on oil prices for the 1986–2009 period. All the estimated structural parameters have the expected sign and are significant at standard test levels. We find that OPEC exercised its market power during the sample period. Counterfactual experiments indicate that world GDP is the main driver of long-run oil prices, however, supply (depletion) factors have become more important in recent years.

JEL Classification: L13, L22, Q31

Keywords: Oil, dominant firm, market power, OPEC, Lerner index, oil demand elasticity, oil supply elasticity.

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1 Introduction

Oil prices have changed substantially over the last three decades. Researchers have considered many explanations to account for the long-run behavior of prices, including growing demand from emerging economies, noncompetitive motives by OPEC, resource depletion, and rising extraction costs. To understand which factors are paramount in driving the oil price requires the estimation of cost and demand parameters under different market structures. Because supply relations and demand function are likely to move simultaneously as a result of exogenous shifters (like income and technological factors), econometric methods such as instrumental variables should be used to estimate these parameters. Unfortunately, the application of these methods to the oil market has proven difficult.[1] We use the dominant firm–competitive fringe textbook model (OPEC versus the group of non-OPEC producers) and estimate significant elasticities over the sample period 1986-2009 that correct for the simultaneity bias by using standard IV methods. We document that OPEC exercised market power during the sample period. We show that it is critical to correctly specify the market structure to obtain significant elasticities.

In our model, demand is standard, depending on the current oil price and world GDP, but we depart from standard supply analysis by assuming that one group of oil producers, OPEC, can exert market power, whereas the non-OPEC oil producers act as a competitive fringe. Once OPEC sets the price of oil, total demand and the fringe's supply are determined, and OPEC is faced with the residual demand: total demand less the competitive supply. OPEC sets the price that maximizes its total profits, taking into account the impact of its pricing decision on the residual demand. This choice leads to a *nonlinear* price-setting rule. We use quarterly data from 1986 to 2009 and estimate a simultaneous system of three equations, using nonlinear instrumental variable methods with world GDP, the production costs for OPEC and non-OPEC producers as exogenous demand and supply shifters. Our results suggest that the nonlinearity induced by OPEC's markup is of key importance in modeling oil prices.

Our results suggest that the dominant firm model provides a fair representation of the oil market: all structural parameters have the expected sign and are statistically significant with exceptional of OPEC marginal cost elasticity. We estimate a long-run price elasticity of demand of -0.39, which is somewhat larger than previous estimates reported in the literature; see, for example, Dahl (1993), Gately and Huntington (2002), and Cooper (2003). Our estimate of the income elasticity of demand is 1.52, which is higher than previous estimates in the Gately and Huntington 2002 study (0.55 for OECD

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[1] Hamilton (2009) summarizing the literature writes "In any given year, both the demand curve and supply curve are shifting as a result of these factors (income and last year's prices, supply factors and others), and one cannot simply look at how price and quantity move together to infer anything about the slope of either curve. The common methodology of including lagged dependent variables in OLS regressions to distinguish between short-run and long-run responses is also problematic."

countries and 1.17 for non-OECD countries including China and India), Graham and Glaister (2004), and other studies. This result partly reflects the high GDP growth rates of China and India during most years of our 1986–2009 data period, which is not a feature in most of the previous studies. We find a non-OPEC supply elasticity of 0.25, and further that the marginal cost of oil production is lower for OPEC than for non-OPEC producers. Because the demand and non-OPEC supply elasticities are statistically significant, we obtain a tight estimate for the degree of OPEC's market power—we find evidence that OPEC exerted substantial market power in the period analyzed.

To gain insight about the role of OPEC's markup for our estimation results, we reestimate the model under the assumption that OPEC is a price taker. With a competitive model we obtain an insignificant (and marginally positive) demand elasticity—a similar result has been obtained in some previous studies, such as Lin (2011). Using the competitive model we also obtain a lower income elasticity (around 0.5) and find an insignificant factor price elasticity for OPEC. The difference between the results obtained from the competitive model and the dominant firm model reflects the nonlinear response induced by OPEC's markup on its residual demand. In our model OPEC's markup is *not* a constant; it is a function of parameters (to be estimated) and endogenous variables.

Using our estimates, we examine the contribution of world GDP and production costs to the long-run trend in oil prices and quantities during our sample period from 1986 to 2009. We find that changes in world GDP explain most of the growth in oil prices and quantities, but the recent rise in production costs is also responsible for higher prices after 2004.

We make three contributions to the literature on crude oil prices. First, there is a large literature on estimating the relationship between oil demand and the price of oil and also the relationship between supply of oil and the price of oil; see, for example, Griffin (1985), Kaufmann (2004), Hansen and Lindholt (2008), Kaufmann et al. (2008), and Bremond et al. (2012). These papers do not account for the simultaneity of supply-and-demand changes. Hamilton (2008) argues that for some periods these estimates are probably good approximations, but in general they are subject to instabilities. Studies that have taken an instrumental variables approach, as we do, are scarce–some examples are Alhajji and Huettner (2000), Almoguera and Herrera (2007), and Lin (2011). We contribute to this literature by providing significant demand and supply elasticities using a simple nonlinear system IV estimator.

Second, our paper is related to the literature that tests different market structures in the oil market; more specifically, the degree to which OPEC can control prices. Griffin (1985) is a seminal paper in this field. In testing whether OPEC is a cartel, Griffin starts out assuming that OPEC is a dominant firm that sets the price of oil. However, the residual demand function, as well as a first-order condition for OPEC, are *not* part of the empirical model. Alhajji and Huettner (2000) and Hansen and Lindholt (2008) also refer to the dominant firm model, but once again, OPEC's price-setting rule is *not* part of the empirical model in these papers. To the best of our knowledge, the present paper is the first one to estimate the simultaneous dominant firm model for the oil market.

Whereas Griffin (1985) concludes that most OPEC countries act as members of a cartel, evidence of OPEC's ability to influence the price of oil is mixed. Papers in the 1980s and 1990s argued in favor of collusive behavior, see Almoguera and Herrera (2007), but later studies, using extended data, found mixed evidence of whether OPEC has exerted market power. For example, Spilimbergo (2001) finds no support for the hypothesis that OPEC, except for Saudi Arabia, was a market-sharing cartel during the 1983–1991 period, whereas Smith (2005) finds that OPEC's market behavior lies between a non-cooperative oligopoly and a cartel. For other studies, see Jones (1990), Gulen (1996) and Bremond et al. (2012), and also Smith (2009) for a review of the literature.

Third, using the model's parameters we show that growth in world GDP has been the main driving force of oil price increases over the last two decades, but that recently rising production costs have contributed significantly to higher oil prices. To the best of our knowledge, we are the first to document the relative importance of *demand and supply factors* for the long-run behavior of oil price. In contrast, some studies, like Killian (2009), assume that supply is fixed, which is reasonable in the short run. Our paper also complements results from the empirical industrial organization literature on measuring the extent of market power (see Bresnahan (1989) for a survey). Our work is closest to Suslow (1986), which documents market power in the aluminium industry.

The paper is divided into six sections. In Section 2 we provide an overview of the crude oil market, and in Section 3 we describe the empirical framework used to estimate the model. Our main results are presented in Section 4. Here we compare our estimated elasticities to those reported in the literature and discuss the fit of the model. We also analyze the relative importance of world income and costs of extraction as the driving forces of the oil price. In Section 5 we perform a number of robustness checks. Section 6 concludes.

2 The Crude Oil Market

In this section we describe the data sources and characterize the crude oil market, focusing mainly on the period that will be analyzed later in the paper.

2.1 Data

We use quarterly data for the period 1986:Q1–2009:Q4. The price of crude oil is measured by the price of Saudi light crude oil, which we obtained from the OPEC Annual Statistical Bulletin 2012 (henceforth OPEC 2012). Nominal prices are deflated by the U.S. CPI, see U.S. Bureau of Labor Statistics (2012a). Data on oil production and the total stock of crude oil in OECD countries were obtained from the EIA Monthly Energy Review (2012). World production of crude oil plus the change in the OECD stock of crude oil is used as a measure for total consumption of (demand for) crude oil.[2]

Our data on OPEC's production costs combine annual data (for the period 1986-2000) in Hansen and Lindholt (2008) and quarterly data (for the period 2001-2009) from IHS CERA. The latter covers the costs of exploration, development, and production. For non-OPEC production costs we use U.S. costs of production, which we believe is a conservative estimate: among the non-OPEC producers, U.S. producers have the highest cost, see Alhajji and Huettner (2000). The source for the non-OPEC cost of production is U.S. Bureau of Labor Statistics (2012b) which compiles a Producer Price Index for production costs in the United States. We set the nominal production cost for non-OPEC suppliers to 10 dollars per barrel in 1999:Q2 (IHS CERA, 2000). Like Kaufmann (2004) and Kaufmann et al. (2008) we also use data for OPEC extraction capacity; these are obtained from Kaufmann (2005). Finally, we use the quarterly world GDP index from Fagan, Henry, and Mestre (2001), and then we transform it into levels using annual GDP from the World Bank (2013). The series is deflated by the U.S. CPI.

2.2 Development in the oil market

In this subsection we describe the main price development in the global oil market since 1973.

Panel (a) in Figure 1 plots the real price of oil (measured in 1996 USD). The figure covers most of the turbulent period between 1973 and 1986, encompassing the huge increase in the oil price that occurred in 1973 when prices rose from 14 to 33 USD per barrel (frequently referred to as OPEC 1). It also includes the sky-high prices around 1979–1980 of roughly 70 USD per barrel (OPEC 2), and the substantial decrease in the oil price during the first half of the 1980s. It is beyond the scope of the present article to discuss this early period — the price path in this period probably reflects structural shocks on the supply side. Rather, our focus centers on the period after 1985, which we believe is characterized by less abrupt changes in the crude oil market.

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[2] Ideally, we would have used the change in world stock of crude oil, but we do not have these data. Because the change in the OECD stock of crude oil amounts to roughly one percent of world crude oil extraction, we believe our approximation of total demand for crude oil is good.

As seen from panel (a), the real oil price was roughly in the range of 15 to 25 USD per barrel from 1986 to 1998, except for the peak in 1990:Q3–1991:Q1, a rise that can be attributed to supply disruptions stemming from the Gulf War. Beginning in 1999, the oil price increased steadily and peaked at 88 USD per barrel in 2008:Q2, then dropped to around 40 USD due to the financial crisis.

Panel (b) shows that the total production of oil has increased steadily after 1985. In this period, non-OPEC production did not change much, but there was a drop in production in the early 1990s, reflecting the contraction of the energy industry in the former Soviet Union. The two plots in panel (b) imply that the OPEC's market share increased from 30 percent in 1986 to 40 percent in 1992 (see Figure 1 panel (c)), where it has largely remained since then.

Figure 2 illustrates the growth in world GDP and China and India's combined share of world GDP. As seen from Figure 2, world GDP increased steadily over the 1986–2009 period, with an average annual growth rate of 2.3 percent. China and India's share of world GDP (measured by the right vertical axis) increased from 2.5 percent in 1986 to 5 percent in 2000, and then reached 12 percent in 2009, reflecting China's fast growth.

Figure 3 plots non-OPEC and OPEC production costs (measured in 1996 USD per barrel). The difference in production cost between these two groups of oil producers narrowed significantly after 1985. The real cost of non-OPEC production decreased steadily after 1985, but increased so much after 2005 that non-OPEC production costs in 1986 and 2009 are almost equal. This development starkly contrasts with OPEC production costs, which increased from 2 USD per barrel in 1986 to 10 USD per barrel in 2009. In fact, since 2005 production costs have increased more for OPEC than for non-OPEC producers.

Figure 4 provides information about changes in world GDP relative to changes in world oil consumption. As seen from the figure, the 1977–1985 period is characterized by a negative relationship between the change in world GDP and the change in world oil consumption. Previous papers (Gately and Huntington, 2002; Griffin and Schulman, 2005) examining this period, which is characterized by high oil prices but low world GDP growth rates, therefore estimated a negative income elasticity. In the 1986–1997 period, oil consumption grew (in percentage) half as fast as world GDP, despite the fact that the oil price did not change much. Oil consumption grew also in the 1998–2009 period about half as fast as world GDP, but during this period the oil price increased significantly.

One simple way to examine the relationship between global oil consumption and world GDP is to calculate the ordinary least squares (OLS) estimate for the correlation between changes in world GDP and changes in world oil consumption. As shown in Figure 4, we obtain 0.53 for 1986–1997 and 0.54 for 1998–2009 (-0.65 for 1973–1985), suggesting that the income elasticity of the price of oil did not change significantly over the 1986–2009 period. Therefore, it seems reasonable to specify a constant income elasticity in the econometric model. We return to this issue in Section 5.

3 Empirical Models for the Crude Oil Market

In this section we present two structural models for the crude oil market that differ in the degree to which OPEC exerts market power. We start by describing the building blocks common to both models, such as world demand and the non-OPEC competitive supply. Then, for the competitive model we assume that OPEC takes the price as given. Finally, we introduce the dominant firm model where OPEC sets the price of oil.

3.1 Theoretical framework

Consider the inverse demand function for oil,

$$P = P(Q^w, Y), \tag{1}$$

where P is the real price of oil, Q^w is world demand for oil, and Y is world GDP.

We assume there are two groups of oil producers, OPEC countries (o) and non-OPEC countries (no). The latter group is assumed to be price takers, and thus its first-order condition, derived from profit maximization, requires that the oil price is equal to the marginal cost (MC) of production:

$$P = MC^{no}\left(Q^{no}, W^{no}, T^{no}\right). \tag{2}$$

Here, Q^{no} is non-OPEC production, which we assume has an increasing marginal cost, W^{no} is the input cost for non-OPEC producers, and T^{no} is a measure of other factors that may have impact on cost of production, for example, resource availability and technological progress.

Below we consider two alternative hypotheses for OPEC production: (i) OPEC has market power (the benchmark case) and (ii) OPEC is a price taker. In the latter case, the first-order condition for OPEC is of course similar to (2):

$$P = MC^{o}\left(Q^{o}, W^{o}, T^{o}\right), \tag{3}$$

where

$$Q^o = Q^w - Q^{no} \tag{4}$$

is OPEC production ($\frac{\partial MC^o}{\partial Q^o} > 0$).

Alternatively, OPEC is not a price taker. This hypothesis takes into consideration that

OPEC's production has an impact on the price of oil: if OPEC production increases, then, *ceteris paribus*, the price of oil will decrease, and therefore non-OPEC extraction will decrease. Formally, equation (2) can be rewritten as $P\left(Q^o + Q^{no}\right) = MC^{no}\left(Q^{no}, W^{no}, T^{no}\right)$, which implicitly defines the function $Q^{no} = Q^{no}\left(Q^o\right)$ where

$$\frac{dQ^{no}}{dQ^o} = -\frac{\frac{\partial P}{\partial Q^w}}{\frac{\partial P}{\partial Q^w} - \frac{\partial MC^{no}}{\partial Q^{no}}} < 0. \tag{5}$$

OPEC maximizes profits, taking (5) into account, that is, OPEC maximizes $P(Q^o + Q^{no}\left(Q^o\right))Q^o - c^o\left(Q^o, W^o, T^o\right)$ with respect to Q^o, where $c^o\left(Q^o, W^o, T^o\right)$ is the total cost of OPEC production. Under the assumption of an internal solution, that is, positive production from both OPEC and non-OPEC producers, OPEC's first-order condition can be specified as price should be a markup above marginal cost,

$$P = m\left(\epsilon, \gamma, s^o\right) MC^o\left(Q^o, W^o, T^o\right), \tag{6}$$

where the markup m is defined as

$$m\left(\epsilon, \gamma, s^o\right) = \frac{\epsilon - (1 - s^o)\gamma}{s^o\left(1 + \gamma\right) + \epsilon - \gamma} = \frac{1}{1 + \frac{1}{\epsilon^o}}. \tag{7}$$

Here, $\epsilon = \left(\frac{\partial P}{\partial Q^w}\frac{Q^w}{P}\right)^{-1} = \frac{\partial Q^w}{\partial P}\frac{P}{Q^w} < 0$ is the demand elasticity, $\gamma = \left(\frac{\partial MC^{no}}{\partial Q^{no}}\frac{Q^{no}}{MC^{no}}\right)^{-1} = \frac{\partial Q^{no}}{\partial P}\frac{P}{Q^{no}} > 0$ is the supply elasticity of non-OPEC producers, and $s^o = \frac{Q^o}{Q^w}$ is OPEC's market share of production. The markup's numerator is negative, and hence the denominator also has to be negative in order to ensure a positive markup. Note that $m\left(\epsilon, \gamma, s^o\right) = \left(1 + \frac{1}{\epsilon^o}\right)^{-1}$, where ϵ^o is the elasticity of the residual demand facing OPEC.[3] Because an internal solution of the OPEC optimization problem requires $\epsilon^o < -1$ (in equilibrium), the corresponding requirement of the markup is $m > 1$; our parameter estimates meet this condition, see Section 4.1.1 The markup is, *ceteris paribus*, increasing in s^o and ϵ, but decreasing in γ. Because the markup is nonlinear in the parameters to be estimated, a nonlinear methodology is required.

An alternative representation (see Bresnahan (1982)) of the first-order condition, which we will use later, is given by

$$P = MC^o\left(Q^o, W_t^o, T_t^o\right) - \lambda\frac{\partial P}{\partial Q^w}Q^o, \tag{8}$$

where

$$\lambda = 1 + \frac{dQ^{no}}{dQ^o} = \frac{\epsilon}{\epsilon - \gamma\left(1 - s^o\right)} > 0, \tag{9}$$

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[3] The elasticity of the residual demand facing OPEC is $\epsilon^o = \frac{\epsilon - \gamma(1 - s^o)}{s^o}$.

where λ is referred to as the market power index. This index embeds several cases: $\lambda = 0$ corresponds to perfect competition, $\lambda = 1$ corresponds to monopoly, and $0 < \lambda < 1$ corresponds to intermediate cases like Cournot competition and a dominant firm with a competitive fringe (our benchmark case).[4]

3.2 Empirical Implementation

Under both market structures (dominant firm and competitive), we have a simultaneous system of equations that determine oil production in OPEC and non-OPEC countries, total oil production, and the world price of oil. To fit the model to the data, the next step is to incorporate specific functional forms.

3.2.1 Specification

We assume that world (w) demand for oil is given by a log-linear function:

$$\ln Q_t^w = \alpha_0 + \alpha_1 \ln P_t + \alpha_2 \ln Y_t + \alpha_3 V_t^w + \alpha_4 D_t + u_t^w, \tag{10}$$

where D_t is a vector of dummies. Further, u_t^i, $i = w, no, o$, is an error term assumed to be independent and identically distributed with zero mean and variance σ_i^2. V_t^w is a vector of demand shifters other than world income. This vector includes lagged differences of $\ln Y$ to correct for second-order biases caused by nonstationary vectors; see Stock and Watson (1993).[5] Demand theory suggests that $\alpha_1 = \epsilon < 0$ and $\alpha_2 > 0$.

The non-OPEC group is a price taker, and they therefore set marginal cost equal to price, see equation (2). Assuming that marginal cost is log-linear[6], the supply of non-OPEC production is also log-linear:

$$\ln Q_t^{no} = \beta_0 + \beta_1 \ln P_t + \beta_2 \ln W_t^{no} + \beta_3 V_t^{no} + \beta_4 D_t + u_t^{no}, \tag{11}$$

where $\beta_1 = \gamma > 0$ and $\beta_2 < 0$ according to standard economic theory. Further, W^{no} is the input cost of non-OPEC production, and V_t^{no} is a vector of (other) supply shifters for non-OPEC.

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[4] As pointed out in Bresnahan (1982), if both demand and marginal cost are linear in quantity, then estimation of a relation of type (8) will identify the *gross* effect of quantity, which consists of two terms: the unit cost of OPEC production and the factor $\lambda \frac{\partial P}{\partial Q^w}$. Hence, it is not possible to identify λ.

[5] To test whether there is cointegration in the data we proceed in two steps. First, we show that five out of the six variables used in the estimation are nonstationary. We applied the standard augmented Dickey-Fuller (ADF) test. We show that for all variables we cannot reject the null hypothesis of a unit root at the 5% significance level. Then, we establish that there are up to five cointegration relationships in the data. We use the Johansen unrestricted cointegration rank test (trace test). We find that the null hypothesis of no cointegrating vector (rank$(\Pi) = 0$) is strongly rejected, and that there is some evidence of more than three cointegrating vectors. See more details in the Appendix A.1.

[6] Implicitly, we allow for non-homothetic cost function in factor prices and output. Constant return to scale technology would imply independence of the marginal cost with respect to production.

Also for OPEC we assume that marginal cost is log-linear. We consider two alternative hypotheses for OPEC (see Section 3.1). First, OPEC acts competitively, and thus its supply function is given by

$$\ln Q_t^o = \pi_0^c + \pi_1^c \ln P_t + \pi_2^c \ln W_t^o + \pi_3^c \ln cap_t^o + \pi_4^c V_t^o + \pi_5^c D_t + u_t^o, \tag{12}$$

where V_t^o is a vector of supply shifters for OPEC, which includes lagged differences of $\ln W^o$ (input cost of OPEC production). In (12) we have used the extraction capacity of OPEC ($\ln cap^o$) as a measure of other factors that may have impact on cost of production, that is, cap^o corresponds to T^o in (3). The basic idea is that cost of production depends on the geology of the oil fields; whether it is cheap or costly to extract oil. If, hypothetically, an oil producer does not find more oil and he extracts from the cheapest fields before he moves on to more expensive fields, then cost of production should increase over time. Alternatively, if more fields are discovered and these have lower costs than the remaining non-exhausted fields, or the rate of technological progress in oil extraction exceeds the rate of technological progress for the general economy, then cost of extraction should decline over time. Due to limited data, we use OPEC capacity to pick up this "time trend". Note that economic theory cannot be used to sign this trend.[7]

Alternatively, OPEC acts as a dominant firm with a competitive fringe—the non-OPEC suppliers. Then, quantity is set so that the price exceeds the marginal cost of production. Using equations (6), (7), (10), and (11), we obtain

$$\ln P_t = \pi_0^d + \ln m\left(\alpha_1, \beta_1, s_t^{no}\right) + \pi_1^d \ln Q_t^o + \pi_2^d \ln W_t^o + \pi_3^d \ln cap_t^o + \pi_4^d V_t^o + \pi_5^d D_t + u_t^o \tag{13}$$

where

$$m\left(\alpha_1, \beta_1, s_t^o\right) = \frac{\alpha_1 - (1 - s_t^o)\beta_1}{s_t^o\left(1 + \beta_1\right) + \alpha_1 - \beta_1}.$$

It is crucial that the markup is a *nonlinear* function of the parameters α_1 and β_1. The model is therefore nonlinear in the parameters to be estimated—this topic is explored in the next subsection.

Using the specified functional forms, the market power index becomes (see (9))

$$\lambda = \frac{\alpha_1}{\alpha_1 - \beta_1(1 - s^o)} > 0. \tag{14}$$

We will use this expression to measure the degree of market power exerted by OPEC.

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[7] Due to lack of data, we have no empirical measure of T^{no}.

3.3 Estimation Methods

Now we describe how we estimate the parameters under the two alternative market structures. First, in the competitive model where OPEC is a price taker, we estimate the structural parameters $\theta^c = [\alpha, \beta, \pi^c]$ using equations (10), (11), and (12). Then, for the dominant firm specification, where OPEC charges a markup over the residual demand, we estimate the parameters $\theta^d = \left[\alpha, \beta, \pi^d\right]$ using equations (10), (11), and (13). In both cases, the vector of instrument variables is[8]

$$Z_t = [\ln Y_t, \ln W_t^{no}, \ln W_t^o, \ln cap_t^o].$$

When OPEC is assumed to be a price taker, the moment condition function $\mathbf{g}(\theta^c)$ is defined as

$$\mathbf{g}(\theta^c) = \left[\begin{array}{l} Z_t \left(\ln Q_t^w - \mathbf{X}^{w\prime}\alpha\right) \\ Z_t \left(\ln Q_t^{no} - \mathbf{X}^{no\prime}\beta\right) \\ Z_t \left(\ln Q_t^o - \mathbf{X}_c^{o\prime}\pi^c\right) \end{array}\right],$$

where $\mathbf{X}^w$, $\mathbf{X}^{no}$, and $\mathbf{X}_c^o$ are vectors of the right-hand side variables in equations (10), (11), and (12), respectively. When estimating this system of three equations, we use three-stage least squares (3SLS). The parameter estimates $\widehat{\theta}^c$ are obtained by solving

$$\widehat{\theta^c} = \arg\min_{\theta^c} \mathbf{g}(\theta^c)'\widehat{W}\mathbf{g}(\theta^c),$$

where the weighting matrix $\widehat{W}$ is evaluated at $(Z'Z)^{-1}$ in the first step and at $(Z'\widehat{\mathbf{u}}\widehat{\mathbf{u}}'Z)^{-1}$ in the second step, and $\widehat{\mathbf{u}} = [\widehat{u}_t^w, \widehat{u}_t^{no}, \widehat{u}_t^o]$. Because this model is linear, system general method of moments (GMM) estimation is equivalent to 3SLS.[9]

When estimating the dominant firm model, we use system nonlinear instrumental variable method (henceforth referred to as NLIV) with the following moment condition function,

$$\mathbf{g}(\theta^d) = \left[\begin{array}{l} Z_t \left(\ln Q_t^w - \mathbf{X}^{w\prime}\alpha\right) \\ Z_t \left(\ln Q_t^{no} - \mathbf{X}^{no\prime}\beta\right) \\ Z_t \left(\ln P_t - \ln m\left(\alpha_1, \beta_1, s_t^o\right) - \mathbf{X}_d^{o\prime}\pi^d\right) \end{array}\right],$$

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[8] We have also included the demand and supply shifters V_t^w, V_t^{no}, and V_t^o. The latter may affect costs of extraction for OPEC, for example because of changes in the composition of oil fields.

[9] We have

$$\widehat{\theta}_{3SLS}^c = \left\{X'\left[\widehat{\Omega}^{-1} \otimes Z\left(Z'Z\right)^{-1} Z'\right] X\right\}^{-1} \left\{X'\left[\widehat{\Omega}^{-1} \otimes Z\left(Z'Z\right)^{-1} Z'\right] Q\right\},$$

where $X = \text{diag}([\mathbf{X}^w, \mathbf{X}^{no}, \mathbf{X}^o])$ and $Q = [\ln Q_t^w, \ln Q_t^{no}, \ln Q_t^o]$. Further, $\widehat{\Omega} = \frac{\mathbf{u}'\mathbf{u}}{N}$ is the covariance matrix of the residuals from 2SLS where N is the number of observations. The variance matrix can be obtained from

$$\text{cov}\left(\widehat{\theta}_{3SLS}^d\right) = \left\{X'\left[\widehat{\Omega}^{-1} \otimes Z\left(Z'Z\right)^{-1} Z'\right] X\right\}^{-1}.$$

where $\mathbf{X}_d^o$ is the vector of the right-hand side variables in equation (13) except the markup. The weighting matrix is evaluated at $(Z'Z)^{-1}$. Furthermore, we also impose the constraint $m(\alpha_1, \beta_1, s_t^o) > 0$, reflecting that the *log* function is defined for positive values only[10].

4 Results

In this section we present the paper's main results. First, we show the estimated elasticities for the dominant firm model (our benchmark) and compare these with the estimates from the competitive model. Then, we explore the fit of the dominant firm model and identify which factor has been the main driver of the crude oil price. Third, we provide evidence for OPEC's exertion of market power during the 1986–2009 period.

4.1 Elasticities

Here we report the estimates from our two specifications. The second column in Table 1 shows our estimates for the dominant firm model - equations (10), (11), and (13) - using the nonlinear instrumental variable method. We have included quarterly dummies, one dummy for wars in the Middle East[11] and another dummy for the former Soviet Union[12]. To account for potential cointegration in the data (see Stock and Watson, 1993), we use lag differences of the exogenous variables: $V_t^w = [\Delta \ln Y_t, \ldots, \Delta \ln Y_{t-q}]$ in the demand equation (10), $V_t^{no} = \left[\Delta \ln W_t^{no}, \ldots, \Delta \ln W_{t-q}^{no}\right]$ in the non-OPEC supply equation (11), and $V_t^o = \left[\Delta \ln W_t^o, \ldots, \Delta \ln W_{t-q}^o\right]$ in the OPEC price-setting equation (13).[13] The third column in Table 1 shows the estimates from the competitive model - equations (10), (11), and (12) - using 3SLS. We use the same instruments and dummy variables as in the estimation of the dominant firm model.

Table 1 also presents the overidentification test for the instrument Z_t for the dominant firm model. To test for the validity of the instruments, we use the Sargan-Hansen J-statistic, which equals the value of the GMM objective function evaluated at the estimated parameters. We find a value of the J-statistic of 2.15. The critical value of the chi-square

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[10] The variance of this estimator is given by

$$\operatorname{cov}\left(\widehat{\theta}^d\right) = \frac{1}{N}\left(\widehat{G}'\widehat{W}\widehat{G}\right)\left(\widehat{G}'\widehat{W}\widehat{S}\widehat{W}\widehat{G}\right)\left(\widehat{G}'\widehat{W}\widehat{G}\right)$$

where $\widehat{G} = \frac{\partial g\left(\widehat{\theta}^d\right)}{\partial \theta^d}$ and $\widehat{S} = \frac{1}{N}\sum Z_i \widehat{u}_i \widehat{u}_i' Z_i$.

[11] The war dummy equals 1 for the period of the Iran–Iraq war 1986:Q1–1988:Q2 and also 1 during the invasion of Kuwait (1990III–IV), and is zero otherwise.

[12] The former Soviet Union dummy equals 1 for the period 1986:Q1–1990:Q2, reflecting the contraction of the energy industry in this country during that period, and zero otherwise.

[13] We use the same number of lags in both the dominant firm and the competitive model. The number of lags (five) is based on the AIC index from the dominant firm model, see Section 5 for a discussion on the importance of lags wrt. the estimation results.

distribution with 45 degrees of freedom is 61.7 at the 5% significance level. Hence, we can not reject the null hypothesis of appropriate specification and validity of the instruments.

4.1.1 OPEC as the dominant firm

Price elasticity of oil demand. The crude oil demand elasticity is estimated to be -0.39 (the standard error is 0.02). It is not easy to compare this estimate with previous studies because these are based on different data, techniques, and periods: all these factors may lead to different estimates. Early studies by Dahl and Yücel (1991), Gately and Huntington (2002), Cooper (2003), Dees et al. (2007) among others, relied on OLS and reported statistically significant long-run price elasticities in the range of -0.3 to -0.6. Gately and Huntington (2002) estimated a single demand equation for the 1971–1997 period, and obtained -0.60 as the long-run price elasticity for oil consumption per capita for OECD and -0.12 for fast-growing non-OECD countries.

Similar to our paper, Alhajji and Huettner (2000) also use instrumental variable techniques to estimate the dominant firm model. In their paper, the OPEC price-setting equation (13) is omitted, thereby de facto treating OPEC's production as exogenous. They obtain an estimate of the demand elasticity of -0.25. The difference between their estimate and our benchmark estimate (0.39) reflects i) different data and ii) different estimation framework. First, Alhajji and Huettner (2000) use OECD demand data (not world demand data like we do), quarterly data for the 1973–1994 period (not 1986–2009 like we do) and they use other data for cost of production for OPEC and non-OPEC than we do. Second, by omitting the OPEC price-setting equation in their estimation they do not take into account the effect of the endogenous variables on OPEC's markup. To illustrate the importance of the estimation strategy, we have reestimated our model equation by equation. With OLS the estimated demand elasticity is 0.00, whereas we obtain 0.01 with IV (when the same instruments as in the benchmark case is used). These results clearly show the importance of specifying the market structure.

Income elasticity. We obtain an income elasticity of demand of 1.52. Most previous studies report an income elasticity that is less than one (Dahl and Yücel (1991), Alhajji and Huettner (2000), Brook et al. (2004), Griffin and Schulman (2005), and others). Gately and Huntington (2002) estimate income elasticities for the 1971–1997 period for different types of countries. In that study, the average income elasticity for 25 OECD countries is 0.55, but 1.17 for 11 non-OECD countries characterized by rapid income growth, and 1.11 for 11 oil-exporting countries. This suggests that income elasticities are greater than one for several non-OECD countries, and may therefore partly explain why our estimate, which is based on data for all countries, exceeds one. However, other reasons why we obtain such a high income elasticity may be related to the data period, type of data and number of lags; see the discussion in Section 5.

Non-OPEC supply. For non-OPEC producers we obtain a supply elasticity of 0.25, meaning that a one percent increase in the crude oil price will increase extraction from the non-OPEC producers by 0.25 percent. There are not many estimates of the non-OPEC supply elasticity in the literature. One exception is the Alhajji and Huettner (2000) study that obtained 0.29, which is close to our result. Turning to the factor price supply elasticity of non-OPEC, our estimate is -1.05, that is, a one percent increase in the unit cost of extraction leads to a nearly equal reduction in non-OPEC production.

OPEC price-setting equation. We estimate a marginal cost elasticity for OPEC ($\frac{\partial \ln MC^o}{\partial \ln Q^o}$) of 1.65; this estimate is, however, insignificant at the five percent test level. However, we can still examine whether the slope of marginal cost for OPEC and non-OPEC differs: a simple one-sided t-test suggests that at five percent significance level the slope of marginal cost for non-OPEC is larger than for OPEC. This could be due to competitive advantages since reserves are more accessible and cheaper to exploit in OPEC than in non-OPEC countries. The OPEC factor price elasticity ($\frac{\partial \ln MC^o}{\partial \ln W^o}$) is estimated to 0.99, whereas the elasticity of the marginal cost of OPEC with respect to OPEC capacity ($\frac{\partial \ln MC^o}{\partial \ln cap^o}$) is estimated to -2.73. This estimate, which is significantly different from zero at the 5 percent test level, suggests strong technological progress in extraction of oil and/or discovery of cheaper oil fields among OPEC members.

If OPEC production increases, then, *ceteris paribus*, the market price will fall, which will lower non-OPEC production, thereby modifying the initial price reduction. We call this *equilibrium* effect the OPEC production elasticity ($\frac{\partial \ln P}{\partial \ln Q^o}$), and it is straightforward to identify it in our framework. Our estimate is -0.74, and the standard error is 0.06.[14] Our estimate for the market power index λ is 0.73, which is clearly above zero and sharply estimated.[15] This suggests that OPEC exerts market power; we will return to this issue in Section 4.3.

Finally, using our estimated parameters we find that the OPEC's markup varies between 1.9 and 7.1 with a mean of 4.2, that is, far above one, which is indeed consistent with theory.[16]

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[14] Notice that

$$\frac{\partial \ln P}{\partial \ln Q^o} = \frac{1}{\epsilon^o} = \frac{s^o}{\alpha_1 - \beta_1 (1 - s^o)}.$$

The equilibrium elasticity is evaluated at the mean of the OPEC market share s^o. The standard error is computed using the delta method. Note that $\widehat{\epsilon}^o = -\frac{1}{0.74} < -1$ at equilibrium.

[15] The market power index λ is evaluated at the mean of the OPEC market share s^o. The standard error is computed using the delta method.

[16] Recall that in our estimation we have imposed that the markup is positive, that is, strictly greater than a small epsilon. Our point estimates clearly meet this restriction.

4.1.2 OPEC as a Competitive Supplier

We now turn to the estimation of the competitive model: by comparing the benchmark model with the competitive model we can quantify the misspecification bias induced by not accounting for OPEC taking into consideration that non-OPEC supply depends on its own level of production, see equation (5). The competitive model is estimated using 3SLS.

Demand. As seen from the last column in Table 1, the demand elasticity has the wrong sign, but it is low and insignificant; 0.01 (0.01) versus -0.39 (0.02) in the benchmark case.[17] In the competitive model the estimated income elasticity is 0.51, which is much smaller than the 1.52 estimate in the benchmark case. This suggests that no accounting for non-competitive market structure in the specification leads to bias in the estimates of the demand elasticity and income elasticity.

Non-OPEC supply. The supply elasticity of non-OPEC is estimated to 0.11, which is smaller than in the dominant firm model (0.25). Likewise, the factor price elasticity of non-OPEC is also smaller (in absolute value) when OPEC is assumed to act competitively (-0.43) than in the benchmark case (-1.05).

OPEC supply. When OPEC is assumed to act competitively, its estimated supply elasticity is 0.16, which is small but somewhat higher than the supply elasticity of non-OPEC (0.11). The factor price elasticity of OPEC is insignificantly different from zero.

In summary, the insignificant factor price elasticity of OPEC, as well as the insignificant demand elasticity, should cast doubt about the use of the competitive model and also the use of linear (in logs) models when modeling oil prices. In the remaining part of the paper we therefore focus on the dominant firm model.

4.2 Fit of the Dominant Firm Model

Using the parameters of the dominant firm model we perform two simulation experiments. First, we evaluate the fit of the model, using the exogenous variables for the 1986–2009 sample period. Then, we perform two counterfactual experiments to explore the relative importance of income and cost when explaining the long-run trends of price and quantities.

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[17] The estimate of the demand elasticity in the competitive model can be compared with Krichene (2006), who estimates a simultaneous equations model for world crude oil demand and competitive oil supply. Krichene applies 2SLS to estimate short-run elasticities, and error-correction methods (ECM) to estimate the long-run demand elasticity using annual data from 1970 to 2005. He finds the demand elasticity to vary across countries, ranging from -0.03 to -0.08, which roughly resembles our result for the competitive model; no price effect on demand.

In-sample prediction. Figure *5* shows the in-sample prediction of the dominant firm model, which tracks the main trends in the market reasonably well but understandably misses some deviations from the trend. In particular, the dominant firm model very accurately predicts the increase in world oil consumption to 2005, as well as the fall in oil consumption after 2005. The model also has some success in predicting the trend in non-OPEC supply and accounting for the fall in non-OPEC production after 2005. Finally, the model predicts a steady increase in the oil price beginning in 1995. As expected, the model misses important deviations from the trend, in particular the peak price in the first half of 2008, right before the financial crisis began in July 2008.

We now examine which exogenous factor—world GDP or costs—contributes most to the trends in consumption, non-OPEC supply, and the oil price predicted by the (benchmark) model. Each panel in Figure *6* shows three curves. The solid curves are the predicted paths of quantities and prices, obtained using the estimates of the benchmark model and the paths of *all* exogenous variables. The two other curves are derived from counterfactual experiments. First, we set the level of world GDP to be constant over time (equal to the 1997:Q1 level), and use the benchmark model's estimates and the paths of all other exogenous variables to predict the evolution of the endogenous variables. Second, we set the level of costs to be constant over time (equal to the 1997:Q1 levels), and use the benchmark model's estimates and the paths of all other exogenous variables to predict the evolution of the endogenous variables.

As seen from Figure *6,* keeping GDP constant at its 1997:Q1 level has a large impact on all variables. Consumption and non-OPEC production remain roughly constant and even fall after 2004. Remarkably, most of the predicted increase in the oil price during the last part of the data period is due to higher income: if world GDP had stayed at its 1997:Q1 level, then, according to the model, the oil price in 2009 would have been roughly 50 percent above the 1997 price, whereas the predicted 2009 oil price when world GDP is not kept constant is almost 200 percent above the 1997 price, see panel (c) in Figure *6*. From panels (b) and (c) we see that costs have contributed to a decrease in non-OPEC supply and to a higher oil price in the last five years.

To summarize, the path of world GDP explains most of the increase in the oil price over the 1986-2009 period. Increased extraction costs have, however, contributed to the increase in oil prices during the last five years.

4.3 OPEC's Market Power

So far we have documented that OPEC's market power index is high. Now, we will measure the degree of OPEC's market power in more detail and provide a descriptive indication of the level of profits enjoyed by OPEC using the standard Lerner index.

Recall from Section 3.1 that we can rewrite OPEC's first-order condition as in equation (8) with the market power index given by equation (14). From equation (8) we see that marginal revenue depends not only on total quantity (through $\frac{\partial P}{\partial Q^w}$), but also on the quantity produced by OPEC (Q^o). This relationship has clear implications: once we have identified the structural parameters α_1 (demand elasticity) and β_1 (fringe supply elasticity), calculating the market power index is straightforward. The estimate of λ is 0.726 (at the mean values of the market share) with 0.04 as the standard deviation, see Table 1. This clearly suggests that λ differs from zero.

Is it possible to test whether OPEC has market power? As a first attempt we use a standard Wald test. Then our null hypothesis is that OPEC is a price taker in a competitive oil market; that is, $H_o : \lambda = 0$. The Wald statistic is 1166.7, and thus the null hypothesis of a competitive oil market is rejected at a one percent significance level. However, we cannot test the hypothesis that OPEC acts noncompetitively because our model does not nest the competitive case; we have *assumed* that OPEC is a dominant firm that takes into consideration how the fringe responds to its production decisions, as shown in equation (5).[18] We can, however, compute confidence intervals for the market power index, which will give information about OPEC's degree of market power, in particular how far its market power index is from zero.

Because the market power index is nonlinear in the parameters and is not defined at zero, we rely on bootstrap methods to compute its sampling distribution. In particular, we compute confidence intervals using quantiles from the empirical sampling distribution. First, we use re-sampling methods for the residuals to generate bootstrap data. In each iteration j, $j = 1, \ldots, 10000$, we keep the exogenous variables fixed as in the data, and recompute the endogenous variables $[\ln Q_t^w, \ln Q_t^{no}, \ln P_t]$. Then, for each iteration we estimate the model and use equation (14) to compute $\widehat{\lambda}_j^*$ ($*$ denotes the estimate from the bootstrap process), see Appendix A.2 for more details. The set of all $\widehat{\lambda}_j^*$ is the empirical distribution of $\widehat{\lambda}$. Finally, we construct the 99th percentile confidence interval (one for each year) using the bootstrap sampling distribution of $\widehat{\lambda}$. Figure 7, which shows the confidence intervals for the market power index, reveals a significant degree of OPEC market power. In particular, for the entire sample period the lower ends of the 99th percentile confidence intervals are by far above zero.

As an alternative to use the market power confidence index, we can calculate the standard Lerner index L_t. Using equation (8) we find

$$L_t \equiv \frac{P_t - MC^o}{P_t} = \frac{\lambda_t s_t^o}{-\epsilon}.$$

We find that the Lerner index had a positive trend between 1986 (51 percent) and

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[18] Technically, the null $\mathrm{H}_0 : \lambda = 0$ is not feasible in our model.

1998 (83 percent). This trend is entirely driven by changes in OPEC's market share because in our model the elasticities are constant. Note that $L_t = \frac{1}{-\epsilon^o} = -\frac{\partial \ln P}{\partial \ln Q^o}$, that is, the absolute value of the OPEC production elasticity increased over time in this period. After 1998, the Lerner index varied between 70 percent and 84 percent. For the entire 1986–2009 period, the average Lerner index was 74 percent.

5 Further Analysis

We now examine how our estimates change with respect to different econometric specifications and data used. First, we explore the robustness of our estimates when we allow for different lags in the correction term. Second, we investigate how the estimates vary between subperiods. This shed light on parameter shifts due to structural changes in demand and supply. Third, we study the impact of assuming that consumer prices differ from producer price. Finally, we check whether our estimates change when we use OECD data instead of world data. We use this exercise to compare with previous studies that have used OECD data.

5.1 Lags

It is standard to include lags in oil market studies; for example, Hansen and Lindholt (2004) use 18 lags (monthly data) whereas Kilian (2009) uses 12 lags in his VAR model (quarterly data). Below we therefore discuss the estimates of the dominant firm model under alternative assumptions about number of lags.

In the benchmark case we used five lags; this is the specification with the highest AIC index.[19] Table 2 shows that the estimated coefficients for demand and non-OPEC supply are robust with respect to number of lags. For example, the estimate of the demand elasticity varies between −0.31 (no lag) and −0.40 (two lags). On the other hand, the estimated OPEC parameters are sensitive to the lag specification. For example, the OPEC factor price elasticity is slightly negative and insignificant in the static version of the model (no lag), but around one and significant with at least two lags. The lack of stability may reflect poor data, for example, the covariate OPEC extraction capacity may not be a good measure of the time trend in oil extraction. Alternatively, the model may be misspecified as it does not allow for dynamic behavior; for example, a higher OPEC capacity may be taken as a signal by non-OPEC producers of a permanent increase in future OPEC production, which will lower the price of oil. Non-OPEC producers may then change its extraction path by speeding up present extraction.

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[19] For six or more lags, Matlab was not able to estimate this non-linear model.

5.2 Data period

In our estimations, we assumed constant parameter values over the data period 1986:Q1–2009:Q4. This may be a strong assumption because of structural changes in demand and supply. For example, over time a higher share of crude oil has been used in the transportation sector, which, according to prior studies, has a lower demand elasticity than other oil-consuming sectors (end-user demand and power generation). Similarly, rapid growth in some Asian countries has increased this region's share of global oil consumption—these countries may have a different demand structure than OECD countries, and also a higher income elasticity of oil, see the discussion above. For OPEC, the energy and environmental policy in OECD countries and discoveries of unconventional petroleum deposits in non-OPEC countries may have a powerful impact on its ability to act as a profit-maximizing cartel, which may lead to structural changes on the supply side.

To investigate the variation in the parameters across periods, we divide the data period into two subperiods; 1986–1997 and 1998–2009, and estimate the benchmark model separately for each of these subperiods, see Table 3. When splitting the original time period into two subperiods, the two estimates of the demand elasticity do not differ much (-0.42 versus -0.39) and they are close to the benchmark estimate (-0.39). On the other hand, for the income elasticity the difference in the subperiod estimates is quite large; 1.32 (1986–1997) versus 3.27 (1998–2009). The 1998–2009 estimate probably mirrors the rapid growth of China and India. Interestingly, for non-OPEC we obtain a smaller supply elasticity in the last period, which may indicate more costly extraction. Finally, the OPEC elasticities differ significantly between the subperiods, which may indicate that the model is too simple to mimic OPEC behavior and the dynamics of the oil market, see the discussion above.

5.3 The consumer price of oil

In the analysis we have used the crude oil price as an explanatory variable for both oil producers and oil consumers; this is standard in the literature. However, consumers face a much higher price of oil than producers; the difference reflects costs (and profits) of refineries, costs (and profits) of transport of crude oil and oil products, and taxes (value added, energy and environmental taxes, etc.).

Energy Prices and Taxes from the IEA provides information on consumer prices of oil by country, sector and oil product. Using IEA (1990), IEA (1995), IEA (2002) and IEA (2011) we construct an OECD consumer oil price where we aggregate over sectors (households, services, industry and transport) and oil products (light fuel oil, heavy fuel oil and automotive diesel). We use information from IEA (2010) on consumption of oil products (by sector) as weights. Figure 8 shows the difference between the OECD consumer price of oil and the crude oil price (in 1996 USD). In 1986 the difference was around 55 USD per barrel, and it increased to around 65 USD in the first part of the 1990s. Later, it fell to 50 USD before it peaked at 80 USD in 2007. Roughly, the OECD consumer price of oil is twice as high as the crude oil price.

Ideally, we should use a weighted average of the consumer price of oil for OECD countries and the consumer price of oil for non-OECD countries when estimating demand for oil. Energy Prices and Taxes provides detailed price information for all OECD countries (see discussion above), but the information on non-OECD countries is by far too limited to be of practical use for the present paper. While the consumer price of oil may differ between OECD and non-OECD, for example due to different tax levels, the *changes* in the consumer price of oil may not differ that much between the OECD and the non-OECD; they both depend on the crude oil price, costs of refineries, costs of transport, etc. We therefore believe that using the OECD consumer price of oil as the explanatory variable for OECD as well as for non-OECD oil consumers may provide better estimates than using the crude oil price as the consumer price of oil for all consumers (the benchmark case).

Table 4 shows the estimates when we use the OECD consumer price of oil (instead of the crude oil price) as an explanatory variable.[20] In general, for most elasticities the change is small; the demand elasticity is now –0.47 (–0.39 in the benchmark case), the non-OPEC supply elasticity is 0.16 (0.25 in the benchmark case), and the market power index is 0.83 (0.73 in the benchmark case). Note, however, that the income elasticity is now 0.99 (1.52 in the benchmark case), that is, more in line with other studies, see discussion above.[21]

5.4 OECD countries

Above, we pooled all countries in the world to examine the relationship between global consumption of oil, world GDP, and the price of oil. Due to lack of data, some earlier studies used OECD oil consumption and/or OECD GDP instead of global oil consumption and global GDP to estimate elasticities; see, for example, Alhajji and Huettner (2000) and Almoguera and Herrera (2007).

In order to shed some light on what kind of biases the use of OECD data may lead to, in Table 5 we have reestimated our benchmark model with OECD data for the 1986–1997 period. As seen from Table 5, for some elasticities, for example, the demand elasticity

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[20] In each year the quarterly changes in the OECD consumer price are assumed to be identical to the quarterly changes in the crude oil price.

[21] An alternative view is that changes in oil taxation in OECD countries have differed so much from the development in oil consumer prices in non-OECD countries that the crude oil price is a better proxy for the non-OECD consumer price than the OECD consumer price. In that case we may underestimate the income elasticity by using the OECD consumer price also for non-OECD countries.

and the non-OPEC supply elasticity, the results for the two cases do not differ much, whereas for other elasticities the difference is large. In particular, the estimated income elasticity is now 0.48, which is much lower than the 1.32 estimate obtained with global data. This could reflect the growth in China and India after 1990 (see Figure 2) that OECD data do not pick up.

Finally, the estimate of the non-OPEC supply elasticity using OECD data is slightly lower than the estimate obtained with world data. However, the estimate of the factor price elasticity for non-OPEC is around zero and insignificant with OECD data but clearly negative (-0.62) and almost significant at the five percent test level with world data. This highlights the importance of using world data.

6 Conclusions

Oil prices have changed dramatically over the last decade. Since the work of Griffin (1985), different studies have tested a variety of market structures using different econometric techniques, data, and models. The results have been mixed, with parameters not being robust to the specification of the model or the sample period, or simply insignificant. In particular, the demand elasticity has proven difficult to estimate reliably.

In this paper we estimate a parsimonious dominant firm model for the global crude oil market. OPEC is envisioned to be a dominant firm, setting its price as a markup over residual demand, and non-OPEC countries act as a competitive fringe. The model is estimated using a system of three equations with OPEC's price response being nonlinear (in logs).

We find significant estimates for most of the long-run parameters of the model. In particular, significant demand and non-OPEC elasticities allow us to measure the degree of OPEC's market power. We find evidence that OPEC exerted substantial market power between 1986 and 2009, the period analyzed in this paper. Then, using the same data but instead assuming that OPEC is a competitive producer, we reestimated the model and compared its fit to the data. We find that the competitive model does not capture the specific characteristics of the global oil market. In particular, it fails to obtain significant demand and supply elasticities. We conclude that the linear (in logs) competitive system may lead to a misspecification bias. Using the parameters of the dominant firm model, we show that world GDP has been the main driving force of oil prices over the last two decades. Furthermore, rising production costs have contributed to an increase in oil prices after 2004.

The results in this paper suggest some avenues for further research. First, we used a static model augmented by dynamic factors (lag structure) and found that these were important for OPEC behavior. Therefore, a dynamic approach to understand capacity, production, and pricing seems a natural step. One strand of the literature, which builds on Hotelling (1931), singles out resource depletion as the dynamic factor to explain the path of oil prices. However, attempts to explain long-run prices by focusing on resource scarcity, see, for example, Pindyck (1978), Lin (2010), and Jovanovic (2013), have had limited success; this may reflect the fact that the size of oil reserves has not changed much over the last 30 years - new discoveries have compensated for current extraction (Smith, 2009).[22] An alternative strategy would be to add dynamics to demand (due to financial speculation) or supply (due to inventories). This would add persistency and volatility to prices, thereby providing a foundation for the model to account for the big swings in prices after 2000.

Second, instead of assuming that OPEC acts as a cost-minimizing cartel we could model a game between the OPEC member countries. This would, however, require detailed data on costs of production for each OPEC country; we have no access to such data. Finally, it could be interesting to relax some of the common assumptions used in time series analysis of the oil market, like fixed supply, and specify a cointegration framework with simultaneous demand and supply.

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[22] Although our model builds on oil producers solving a static optimization problem, which is in contrast to the standard approach used in resource economics where a producer of an exhaustible resource solves an intertemporal optimization problem in order to find the path of extraction that maximizes profits, our estimates may still reflect the economic importance of the physical limitation of the stock of oil. The reason is that the solution of the intertemporal optimization problem can be summarized by a marginal resource (scarcity) rent, which can be seen as an additional cost component for the oil producer. The marginal resource rent is positive if either the physical limitation of the resource is binding, that is, the resource owner's profits would increase if, hypothetically, more of the resource was available, or marginal cost of extraction is increasing and the cheapest fields are extracted first, meaning that the more oil is extracted today, the higher the cost of extraction will be tomorrow. In our model OPEC's price-setting rule and non-OPEC's supply function are closely related to their marginal cost functions, and hence the estimated parameters should reflect the marginal resource rent of each group.

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A. Appendix

A.1 Cointegration tests

As mentioned in the main text, to ensure that we describe stable long-run relationships we perform a cointegration analysis of the data. First, we show that five out of the six variables used in the estimation are nonstationary. Then, we establish that there are up to four cointegration relationships in the data. To test variables for unit root we employ the augmented Dickey Fuller (ADF) test. Panel (a) in Table 6 shows the ADF statistics for the six variables used in the estimation. At the 5 percent significance level we cannot reject the null hypothesis of a unit root for non-OPEC production, oil price, world GDP, non-OPEC cost, and OPEC cost. In contrast, the ADF statistics for world consumption rejects the null hypothesis of a unit root.

Next, we test for cointegration using Johansen's unrestricted cointegration rank test (trace test). Unlike the single-equation Engle–Granger test discussed in Kaufmann (2004), the Johansen procedure is designed to identify multiple cointegrating relations among a set of variables.[23] Panel (b) in Table 6 presents the results of Johansen's statistics. We see that the null hypothesis of no cointegrating vector ($\text{rank}(\Pi) = 0$) is strongly rejected, and that there is some evidence of more than three cointegrating vectors. Following Stock and Watson (1993), we add lags of the difference of the exogenous variables to obtain efficient statistical tests of the parameters.

A.2 Construction of confidence intervals

We compute confidence intervals implementing the following steps:

1. Bootstrap data-generating process

   In this step we resample the residuals to generate bootstrap data; that is, we hold the exogenous variables fixed, but make the endogenous variables $[\ln Q_t^w, \ln Q_t^{no}, \ln P_t]$ equal to the expected value $\left[\ln \widehat{Q}_t^w, \ln \widehat{Q}_t^{no}, \ln \widehat{P}_t\right]$ plus a re-sampled residual $u_j^* = \left[u_{tj}^{w*}, u_{tj}^{no*}, u_{tj}^{o*}\right]$. For the jth repetition we use the empirical distribution of the predicted errors (Fox 2008 and MacKinnon 2007):

   $$[\ln Q_t^{w*}, \ln Q_t^{no*}, \ln P_t^*] = \left[\ln \widehat{Q}_t^w, \ln \widehat{Q}_t^{no}, \ln \widehat{P}_t\right] + u_j^*,\ u_j^* \sim EDF\left(\widehat{u}_t\right)$$

   (* denotes bootstrap data). When we use this method we rely on the regression model to obtain the correct conditional expectation, but we do not use the empirical distribution

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[23] The Johansen method essentially works in two stages. First, we regress the vector of variables $\mathbf{x}_t = [Q^w, Q^{no}, P, Y, W^{no}, W^o]$ in a vector error-correction model (VECM)

$$\Delta \mathbf{x}_t = \sum_{i=1}^{k-1} \Gamma_i \Delta \mathbf{x}_{t-i} + \Pi \mathbf{x}_{t-1} + \epsilon_t$$

where Γ_i and Π are matrixes of parameters. The number of cointegrating vectors is then identical to the number of stationary relationships in the Π-matrix, which is determined by the rank of the Π matrix.

of errors. As discussed by MacKinnon (2007), in bootstrap hypothesis testing the data should be resampled under the null hypothesis.

2. We estimate the dominant firm model using bootstrap data and use (14) to compute $\widehat{\lambda}_j^*$.
3. We construct the 99th percentile interval using the quantiles of the bootstrap sampling distribution of $\widehat{\lambda}^* : \widehat{\lambda}^*_{0.5\%} < \lambda < \widehat{\lambda}^*_{99.5\%}$.

Table 1: Estimates for the Dominant Firm and the Competitive Model

Models	Dominant firm NLIV			Competitive 3SLS	
			World Demand		
$\frac{\partial \ln Q^w}{\partial \ln P}$	–0.390	(0.020)		0.008	(0.008)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	1.515	(0.174)		0.508	(0.024)
			Non-OPEC Supply		
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	0.245	(0.034)		0.106	(0.013)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	–1.045	(0.332)		–0.425	(0.103)
			OPEC Supply		
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	1.649	(1.245)	$\frac{\partial \ln Q^o}{\partial \ln P}$	0.163	(0.036)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	0.989	(0.244)	$\frac{\partial \ln Q^o}{\partial \ln W^o}$	–0.037	(0.074)
$\frac{\partial \ln MC^o}{\partial \ln cap^o}$	–2.725	(1.089)	$\frac{\partial \ln Q^o}{\partial \ln cap^o}$	0.663	(0.118)
λ	0.726	(0.038)			
Overidentification test $J \sim \chi^2\,(dof)$					
J-statistic	2.151			1.532	
Degrees of freedom	45			45	

Notes: We use quarterly data, from 1986:Q1–2009:Q4; the heteroskedasticity and autocorrelation consistent (HAC) standard errors are shown in parenthesis. The table reports estimates for elasticities and the market power index λ. The second column shows the results for the dominant firm model, that is, equations (10), (11), and (13), using a nonlinear instrumental variable (NLIV) method. The third column shows the estimates for the competitive model, that is, (10), (11), and (12), using three-stage least squares (3SLS). The predetermined exogenous variables used in the models are $V_t^w = \Delta \ln Y_t, \ldots, \Delta \ln Y_{t-q}$ in the demand equation, $V_t^{no} = \Delta \ln W_t^{no}, \ldots, \Delta \ln W_{t-q}^{no}$ in the non-OPEC supply equation, and $V_t^o = \Delta \ln W_t^o, \ldots, \Delta \ln W_{t-q}^o$ in the OPEC equations, all with $q = 5$. In the dominant firm model, λ is evaluated at the mean of the market share of OPEC, and its standard error is computed using the delta method. The overidentification test of instruments $Z_t = [\ln Y_t, \ln W_t^{no}, \ln W_t^o, V_t^w, V_t^{no}, V_t^o]$ is shown in the lower table. The critical value of the chi-square distribution with 45 degrees of freedom at the 5% significance level is 61.656.

Table 2: Estimates Using Different Number of Lags: the Dominant Firm Model

No.lags q	0 lag Static		2 lags		4 lags		5 lags Benchmark	
				World Demand				
$\frac{\partial \ln Q^w}{\partial \ln P}$	–0.309	(0.018)	–0.403	(0.027)	–0.397	(0.021)	–0.390	(0.020)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	1.351	(0.174)	1.556	(0.199)	1.532	(0.180)	1.515	(0.174)
				Non-OPEC Supply				
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	0.267	(0.032)	0.265	(0.034)	0.250	(0.034)	0.245	(0.034)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	–1.004	(0.254)	–0.996	(0.269)	–1.082	(0.323)	–1.045	(0.332)
				OPEC Supply				
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	4.711	(2.317)	2.591	(1.234)	1.566	(1.227)	1.649	(1.245)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	–0.064	(0.851)	0.963	(0.264)	1.104	(0.217)	0.989	(0.244)
$\frac{\partial \ln MC^o}{\partial \ln cap^o}$	–5.870	(2.124)	–3.607	(1.184)	–2.888	(1.106)	–2.725	(1.089)
λ	0.658	(0.040)	0.716	(0.037)	0.725	(0.037)	0.726	(0.038)
AIC Index	–63.341		–33.915		4.825		36.838	

Notes: We use quarterly data, for the period 1986:Q1–2009:Q4; the heteroskedasticity and autocorrelation consistent (HAC) standard errors are shown in parenthesis. The table reports estimates of elasticities, the market power index λ and the AIC index for the dominant firm model using different number of lags for the lagged differences of the (log) exogenous variables, V_t^w, $V_t^{no}$and V_t^oin equations (10), (11), and (13).

Table 3: Estimates for Different Time Periods: the Dominant Firm Model

Periods	1986-2009 Benchmark		1986–1997		1998–2009	
			World Demand			
$\frac{\partial \ln Q^w}{\partial \ln P}$	–0.390	(0.020)	–0.416	(0.043)	–0.390	(0.026)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	1.515	(0.174)	1.320	(0.253)	3.265	(0.359)
			Non-OPEC Supply			
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	0.245	(0.034)	0.346	(0.057)	0.129	(0.048)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	–1.045	(0.332)	–0.623	(0.335)	–0.499	(0.173)
			OPEC Supply			
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	1.649	(1.245)	0.489	(1.030)	–4.488	(2.036)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	0.989	(0.244)	0.186	(0.924)	1.585	(0.267)
$\frac{\partial \ln MC^o}{\partial \ln cap^o}$	–2.725	(1.089)	–1.120	(0.589)	–8.024	(2.271)
λ	0.726	(0.038)	0.659	(0.052)	0.839	(0.059)

Notes: We use quarterly data; the heteroskedasticity and autocorrelation consistent (HAC) standard errors are shown in parenthesis. The table reports estimates of elasticities and the market power index λ for the dominant firm model – equations (10), (11), and (13).

Table 4: Estimates Using Consumer Price of Oil: the Dominant Firm Model

Prices	Crude oil price (Benchmark)		Consumer price	
		World Demand		
$\frac{\partial \ln Q^w}{\partial \ln P}$	–0.390	(0.020)	–0.473	(0.096)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	1.515	(0.174)	0.989	(0.122)
		Non-OPEC supply		
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	0.245	(0.034)	0.162	(0.030)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	–1.045	(0.332)	–0.698	(0.221)
		OPEC Supply		
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	1.649	(1.245)	2.003	(1.024)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	0.989	(0.244)	0.995	(0.235)
$\frac{\partial \ln MC^o}{\partial \ln cap^o}$	–2.725	(1.089)	–2.797	(1.014)
λ	0.726	(0.038)	0.829	(0.038)

Notes: We use quarterly data from 1986:Q1–2009:Q4. The heteroskedasticity and autocorrelation consistent (HAC) standard errors are shown in parenthesis. The table reports estimates of elasticities and the market power index λ for the dominant firm model using either the crude oil price or the OECD consumer price as an explanatory variable for demand for oil.

Table 5: Estimates with Different Data: the Dominant Firm Model 1986-1997

Data	World data		OECD data	
		World Demand		
$\frac{\partial \ln Q^w}{\partial \ln P}$	–0.416	(0.043)	–0.321	(0.085)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	1.320	(0.253)	0.482	(0.097)
		Non-OPEC Supply		
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	0.346	(0.057)	0.285	(0.094)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	–0.623	(0.335)	–0.053	(0.480)
		OPEC Supply		
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	0.489	(1.030)	–0.113	(0.141)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	0.186	(0.924)	1.133	(0.642)
$\frac{\partial \ln MC^o}{\partial \ln cap^o}$	–1.120	(0.589)	–1.086	(0.512)
λ	0.659	(0.052)	0.562	(0.064)

Notes: We use quarterly data from 1986:Q1–1997:Q4; the heteroskedasticity and autocorrelation consistent (HAC) standard errors are shown in parenthesis. The table reports estimates of elasticities and the market power index λ in the dominant firm model and the competitive model. We use quarterly OECD data for the period 1986:Q2–1997:Q4.

Table 6: Cointegration Test

(a) ADF Test of Unit Root

	No.lag	Test statistic	Critical value at 5%	p–value	Conclusion
World production: Q^w	0	–4.514	–3.459	0.003	I(0)
Non-OPEC production: Q^{no}	0	–1.855	–3.459	0.659	I(1)
Price of oil: P	0	–2.793	–3.459	0.205	I(1)
World GDP: Y	0	–0.768	–3.459	0.964	I(1)
Non-OPEC cost: W^{no}	4	–0.810	–3.461	0.960	I(1)
OPEC cost: W^o	3	–0.170	–3.460	0.992	I(1)

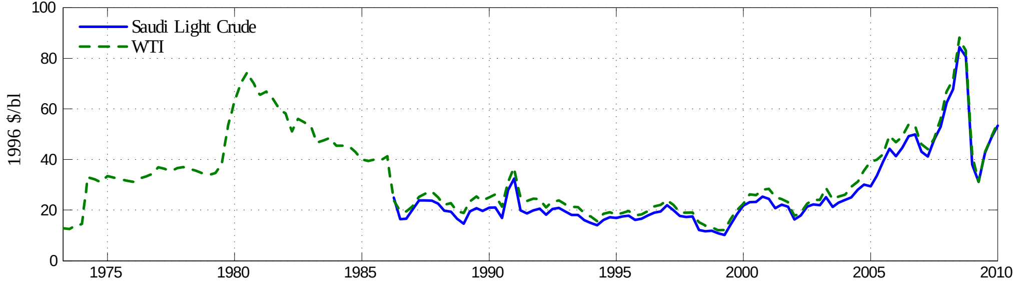
(b) Johanssen Test for the Existence of Cointegration Vectors

Cointegrating rank H_0:rank(Π)=r	0	1	2	3	4	5
Trace statistics	210.210	144.45	98.108	52.880	30.272	13.668
5% critical value	125.620	95.754	69.819	47.856	29.798	15.495
p–value	<0.001	<0.001	<0.001	0.016	0.044	0.093
Obs.	96					
Differenced lags	1					

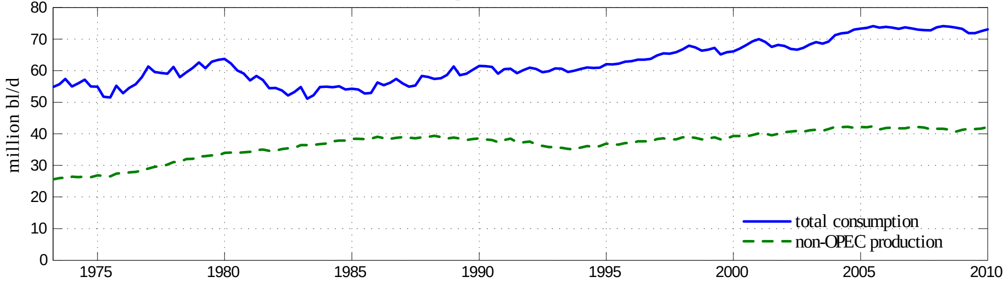
Notes: Table (a) shows the ADF statistics with a drift and deterministic trend for the unit root process of each variable. The number of lags used is selected by the AIC index. The critical value of rejecting the null hypothesis at 5% level and the p-value of the statistics are presented. The conclusion of the ADF test at 5% significance level is listed. Table (b) shows the Johansen test of vector cointegration for different cointegration ranks. This vector includes Q^w, Q^{no}, P, Y, W^{no}, W^o and OPEC extraction capacity. Π is the coefficient for the lagged vector in the VEC model. 96 observations are used in the tests.

Figure 1: Real Price of Oil and Oil Production

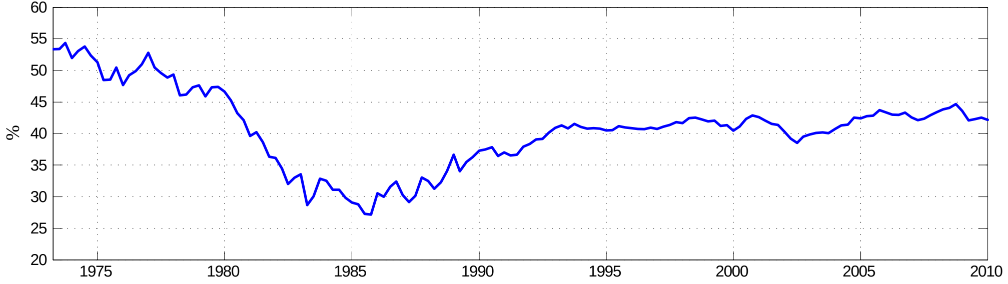
(a) Real Oil Price



(b) World Oil Consumption and Non-OPEC Production

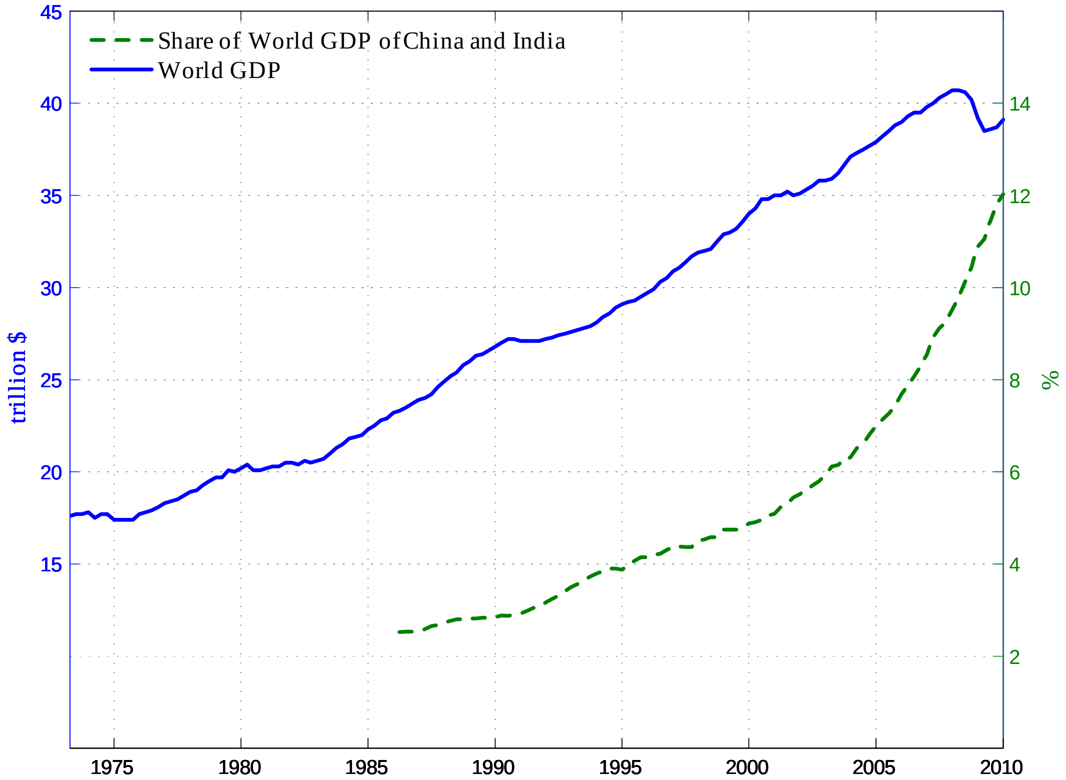


(c) OPEC Market Share



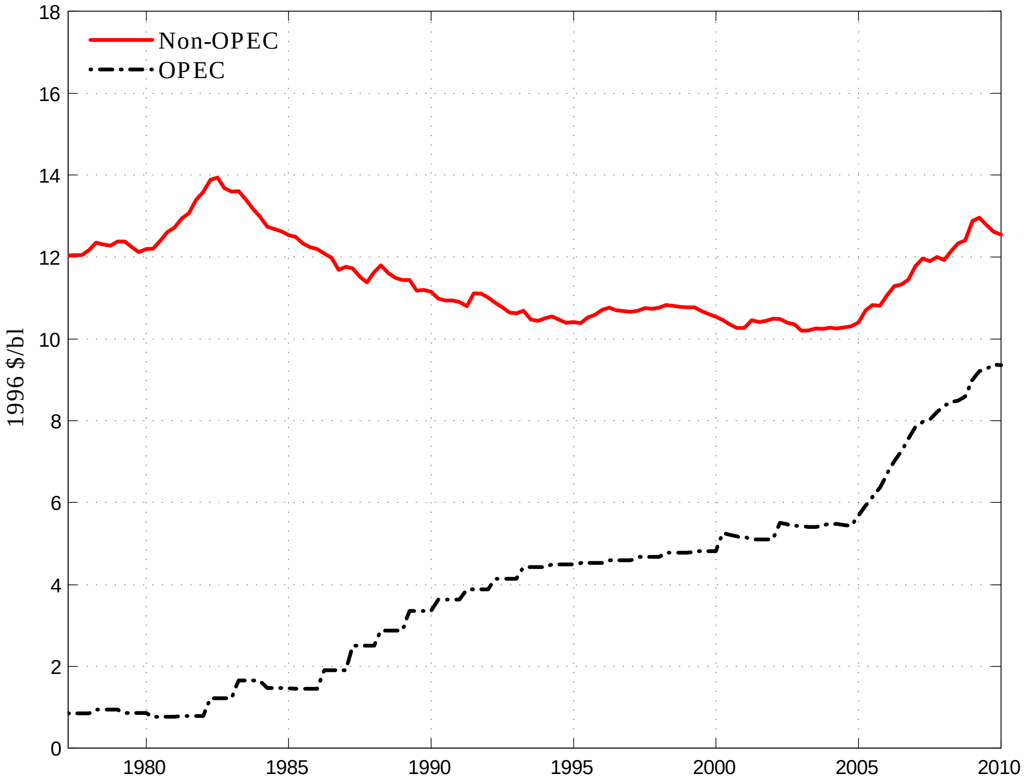
Notes: Panel (a) plots the real Saudi light crude oil price and the WTI price. The nominal Saudi light crude oil price is collected from the OPEC Annual Statistical Bulletin (OPEC, 2012). The nominal WTI price of crude oil is collected from Federal Reserve Bank of St. Louis (2013). Nominal prices are deflated by the U.S. CPI from the U.S. Bureau of Labor Statistics (2012a). Panel (b) plots world oil consumption and non-OPEC production. The world consumption is defined as the sum of world production and OECD inventory changes. All quantity series are collected from the EIA (2012). Panel (c) plots the OPEC production share.

Figure 2: Real World GDP and China and India's Share of World GDP



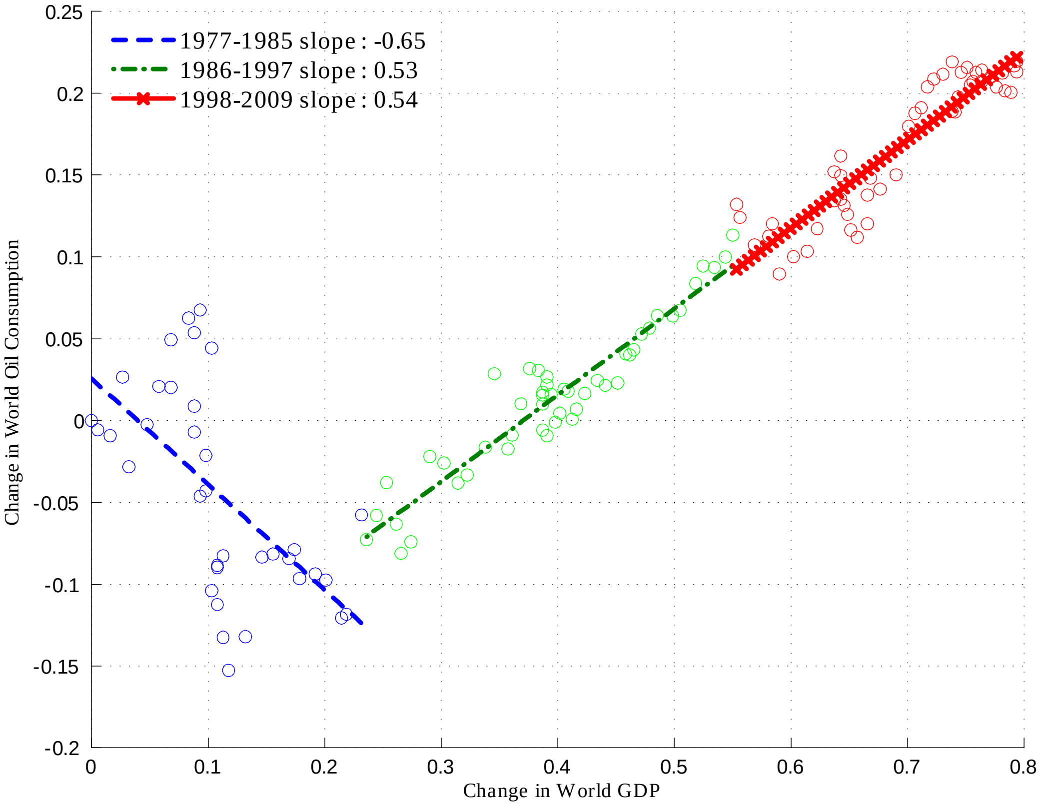
Notes: The figure plots real world GDP (measured by the left vertical axis) and China and India's share of world GDP (measured by the right vertical axis). World GDP is computed using the world GDP index from Fagan, Henry and Mestre (2001) and world GDP from WDI, World Bank (2013).

Figure 3: Real Cost of Production in OPEC and Non-OPEC



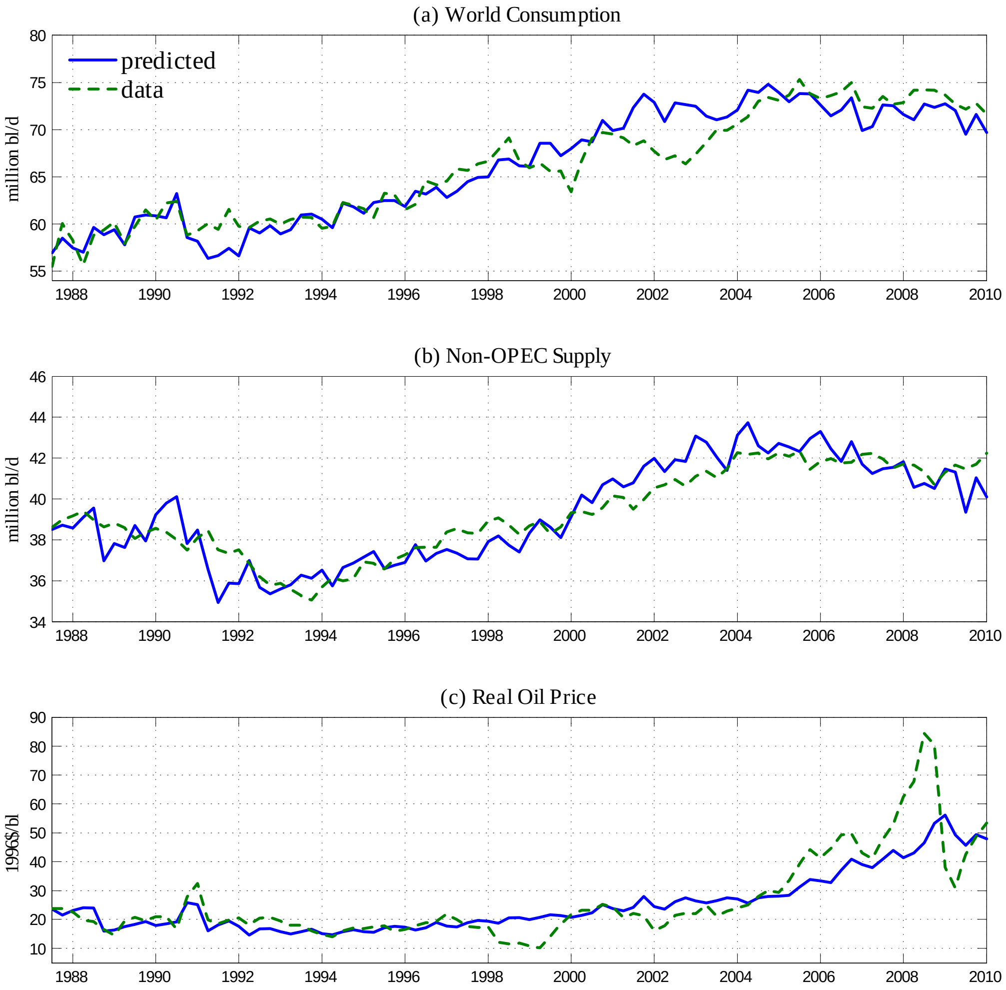
Notes: The OPEC cost is combined with the annual cost of OPEC for 1975–2000 in Hansen and Lindholt (2008) and quarterly observations of exploration, development and production costs for 2001:Q1–2009:Q4 from IHS CERA. The source for the non-OPEC cost is U.S. Bureau of Labor Statistics (2012b). It is a Producer Price Index for production cost in the United States. We set the nominal cost for non-OPEC to 10 USD per barrel in 1999:Q2 (IHS CERA, 2000).

Figure 4: Changes in World Real GDP and World Oil Consumption



Notes: Horizontal axis: cumulative change in natural logarithm of real GDP for different periods. Vertical axis: cumulative change in natural logarithm of total oil consumption. The slope is estimated using OLS with a constant.

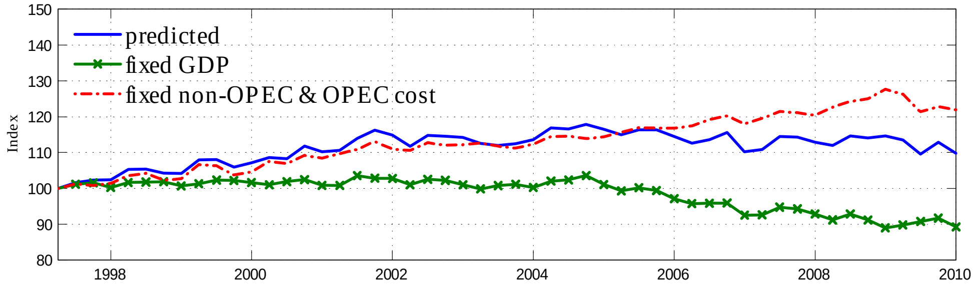
Figure 5: In-Sample Prediction for the Dominant Firm Model



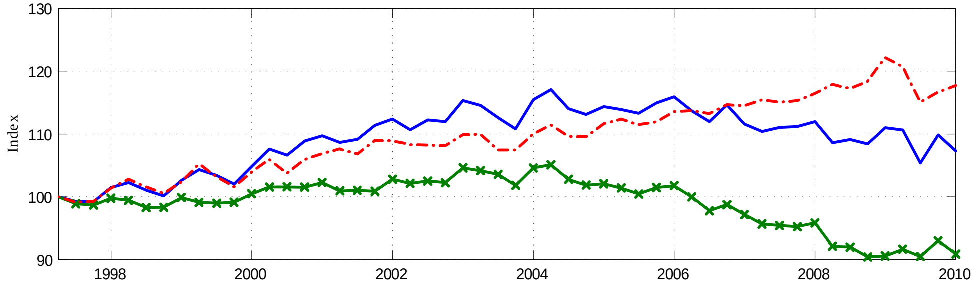
Notes: Panels (a)–(c) plot the in-sample prediction of world consumption, non-OPEC supply, and the real oil price for the dominant firm model.

Figure 6: In-Sample Prediction for the Dominant Firm Model with Constant GDP or Constant Cost of Oil Production

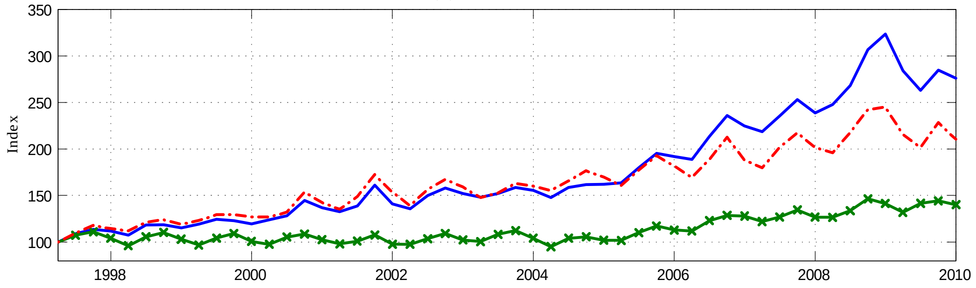
(a) World Consumption



(b) Non-OPEC Supply

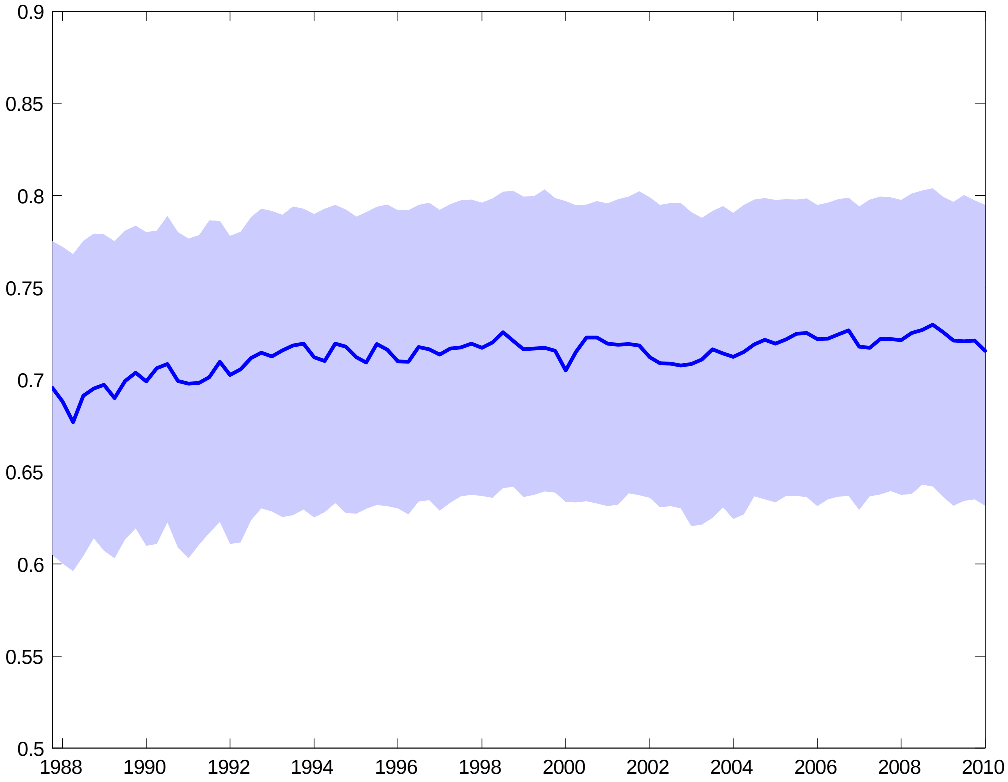


(c) Real Oil Price



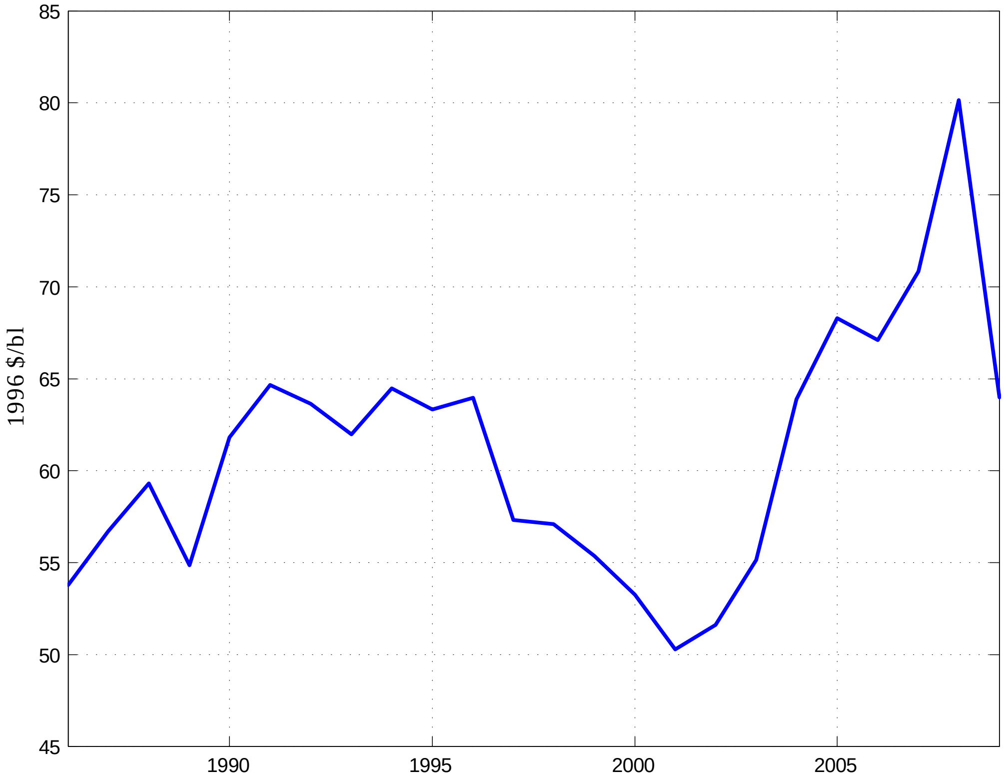
Notes: Panels (a)–(c) show the in-sample prediction of world consumption, non-OPEC supply, and the real oil price for the dominant model in different scenarios. The solid line represents the in-sample prediction with all covariates in the model. The cross-solid line represents the in-sample prediction with fixed world GDP at the 1997:Q1 level. The dot-dash line represents the in-sample prediction with fixed costs of oil extraction in OPEC and non-OPEC at the 1997:Q1 levels. All series are normalized such that their 1997 values are equal to 100.

Figure 7: Bootstrap 99th Percent Confidence Intervals of the Market Power Index



Notes: The figure plots the bootstrap 99th percent confidence intervals using percentiles from the empirical sampling distribution of the market power index $\widehat{\lambda}$. We use a re-sampling method of the residuals to generate bootstrap data. Then we estimate the dominant firm model and compute λ in each repetition. The number of bootstrap repetitions is 10,000.

Figure 8: Difference Between OECD Consumer Price and Crude Oil Price



Notes: The figure plots the difference between the annual OECD consumer price and the annual crude oil price. The OECD consumer price is based on information on consumer prices of oil products from the IEA publication Energy Prices and Taxes, whereas the crude oil price is the yearly average of the quarterly Saudi light crude oil price.