



OPEC's market power: An empirical dominant firm model for the oil market



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ABSTRACT

We estimate a dominant firm-competitive fringe model for the crude oil market using quarterly data on oil prices for the 1986–2016 period. The estimated structural parameters have the expected signs and are significant. We find that OPEC exercised 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.

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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 behavior of OPEC, resource depletion, and rising extraction costs. To understand which factors are paramount in driving the oil price, estimation of cost and demand parameters under different market structures is required. Because supply relations and demand function are likely to move simultaneously as a result of exogenous shifters (such as 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, see [Hamilton \(2009\)](#).

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, 1986–2016. The simultaneity bias is corrected for by using standard instrumental variable (IV) methods. We show that it is critical to correctly specify the market structure to obtain significant elasticities, and document that OPEC exercised market power during the sample period, 1986–2016.

In our model, demand is standard – it depends 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.

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Our empirical model contains a simultaneous system of three equations and is estimated using nonlinear instrumental variable methods with world GDP and production costs for OPEC and non-OPEC producers as exogenous demand and supply shifters. We use quarterly data from 1986 to 2016, which is a period after the major structural changes in the oil market in the 1960s and the 1970s. Our results suggest that the nonlinearity induced by OPEC's markup is of key importance in modeling oil prices.

We find that the dominant firm model provides a good representation of the oil market: all structural parameters have the expected signs and are statistically significant (except for the marginal cost elasticity of OPEC). We estimate a long-run price elasticity of demand of -0.35 , 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 1.15, which is higher than previous estimates, see, for example, the Gately and Huntington (2002) study (0.55 for OECD countries and 1.17 for non-OECD countries including China and India) and Graham and Glaister (2004). We believe our results reflect that China and India, which had high GDP growth rates in the data period, 1986–2016, had high income elasticities in this period.

We find a non-OPEC supply elasticity of 0.32. 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 empirical 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 2016. 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 2005.

We make four 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, Kaufmann et al., 2008 and Brémond et al., 2012). These papers do not account for the simultaneity of supply-and-demand changes. Hamilton (2009) argues that, for some periods, these estimates are probably good approximations, but, in general, they are subject to instabilities. Studies that have taken the simultaneity of supply-and-demand changes into account, as we do, are scarce – some examples are Alhajji and Huettner (2000), Krichene (2002), Almoguera et al. (2011), and Lin (2011). We contribute to this literature by estimating a simultaneous dominant firm-competitive fringe model for the oil market, using the nonlinear instrumental variable method – the nonlinear estimator reflects the nonlinearity of the system of equations to be estimated. We obtain statistically significant demand and fringe (non-OPEC) supply elasticities.

Second, our paper is related to the literature that tests 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, 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 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, for example, Almoguera et al. (2011), 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. Boug et al. (2016) present a model that encompasses several alternative specifications suggested in the literature. They find support for imperfect competition in the oil market, and also that OPEC's behavior has changed significantly over the last years. For other studies, see Jones (1990), Gulen (1996), Brémond et al. (2012), Cairns and Calfucura (2012), Huppmann and Holz (2012), Colgan (2014), Kisswani (2016) and Okullo and Reynès (2016). Smith (2009) and Fattouh and Mahadeva (2013) present reviews of the literature. Our contribution is to test whether OPEC had market power by using a non-nested statistical test for competing models: by comparing our dominant firm model with the competitive model, we find no evidence to reject the dominant firm model.

Third, using the model's estimated parameters, we show that growth in world GDP has been the main driving force of oil price increases over the last three decades, but recent rises in production costs have contributed significantly to higher oil prices. To the best of our knowledge, we are among the first to document the relative importance of *demand and supply factors* for the long-run behavior of oil prices, see Section 4.2. In contrast, some studies, like Kilian (2009), assume that supply is fixed, which is reasonable in the short run.

Finally, our paper complements results from the empirical industrial organization literature on measuring the degree of market power, see, for example, Suslow (1986), which finds substantial market power in the aluminum industry in the period between World War I and World War II. Our measure of market power builds on Bresnahan (1982), and, as reported above, we find clear evidence of exertion of market power in the oil market between 1986 and 2016. For a survey of the literature on industries with market power, see Bresnahan (1989).

Our 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. The main results are presented in Section 4. Here, we compare our estimated elasticities with 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 on the period that is analyzed in this paper.

2.1. Data

We use quarterly data for the period, 1986:Q1–2016:Q4. The price of crude oil is measured by the West Texas Intermediate (WTI), which we obtained from the Federal Reserve Bank of St. Louis (2017).

Nominal prices are deflated by the US CPI, see [U.S. Bureau of Labor Statistics \(2017a\)](#). Data on oil production and inventory of crude oil in OECD countries were obtained from [EIA \(2017\)](#). World production of crude oil plus the change in the OECD inventory of crude oil is used as a measure for total consumption of (demand for) crude oil.¹

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, 2001–2016) from IHS CERA. Both series cover costs of exploration, development and production. For non-OPEC production costs, we use US costs of oil production, which we believe is a conservative estimate: among the non-OPEC producers, US 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 \(2017b\)](#), which compiles a Producer Price Index (PPI) for oil and gas field machinery and equipment 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's installed extraction capacity; these are obtained from [Kaufmann \(2005\)](#) for the period, 1986:Q1–2007:Q3, and from the [IEA Oil Market Report](#) for the period, 2007:Q4–2016:Q4.² Finally, we used the quarterly world GDP index from [Fagan et al. \(2001\)](#) for the period, 1986:Q1–2010:Q4, and Global Financial Data for the period, 2011:Q1–2016:Q4. The series is deflated by the US CPI.

2.2. Development in the oil market

In this subsection, we describe the main development in the global oil market since 1973, and also relate this to economic development. Panel (a) in [Fig. 1](#) plots the real price of oil (measured in 2010 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 18 to 52 USD per barrel (frequently referred to as OPEC 1). It also includes the sky-high prices around 1979–1980 at roughly 100 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 this paper 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 is characterized by less abrupt changes in the crude oil market.

As seen from panel (a), the real oil price was roughly in the range of 20 to 40 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 126 USD per barrel in 2008:Q2, then dropped to around 40 USD due to the financial crisis, but increase again rather rapidly: In 2012–2014, the oil price was close to 100 USD. However, late in 2014, the price dropped; it went down to around 40 USD in 2015–2016.

Panel (b) shows that total production of oil 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% in 1986 to 40% in 1992 (see [Fig. 1](#) panel (c)), where it has remained.

[Fig. 2](#) illustrates the growth in world GDP, and also China and India's combined share of world GDP. As seen from [Fig. 2](#), world GDP increased steadily over the 1986–2016 period, with an average annual growth rate of 2.2%. China and India's share of world GDP (measured by the right vertical axis) increased from 3% in 1987 to 5% in 2000, and then reached 18% in 2016, reflecting China's fast growth.

[Fig. 3](#) plots non-OPEC and OPEC production costs (measured in 2010 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 1983, but increased after 2005. From 2010, the non-OPEC production cost has been around 16 USD per barrel. This development starkly contrasts with OPEC production costs, which increased from 1 USD per barrel in 1986 to 8 USD per barrel in 2008. Then, the OPEC production cost did not change much over the next years, but, in 2016, it dropped to 5 USD per barrel.

We now turn to the relationship between the oil market and GDP. [Hamilton \(2009\)](#), summarizing some studies undertaken between 1991 and 2003, concludes that these suggest an income elasticity near one. He then examines the (partial) relationship between the change in US oil consumption and the growth in US GDP – henceforth termed the income elasticity. He finds income elasticities around 1 for the period, 1949–1973, and around 0.5 for the period, 1985–1997, but a negative income elasticity between 1974 and 1985. We now do the same exercise as [Hamilton \(2009\)](#), but for the entire world (not just the United States).

[Fig. 4](#) provides information about changes in (real) world GDP relative to changes in (real) world oil consumption. As seen from the figure, the 1973–1985 period is characterized by a negative relationship between the change in world GDP and the change in world oil consumption, whereas the opposite is the case for the periods 1986–2000 and 2001–2016.

One simple way to quantify the relationship between global oil consumption and world GDP is to calculate the ordinary least-squares (OLS) estimate for this coefficient. As shown in [Fig. 4](#), the estimate is -0.07 for 1973–1985 (which is a period not included in the data used to estimate our empirical model below), compared with 0.52 for 1986–2000 and 0.64 for 2001–2016. This suggests that the income elasticity of oil did not change significantly over the 1986–2016 period. Therefore, in our empirical model, we impose a constant income elasticity for the period, 1986–2016, but, in [Section 5](#), we estimate the empirical model for subperiods.

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 common building blocks of the 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,

$$P = P(Q^w, Y, V^w), \quad (1)$$

where P is the real price of oil, Q^w is world (w) demand for oil, Y is (real) world GDP and V^w is a measure of other factors that may have an impact on demand for oil.

¹ Ideally, we would have used the change in world inventory of crude oil, but we do not have these data. Because the change in the OECD inventory of crude oil amounts to roughly 1% of world crude oil extraction, we believe our approximation of total demand for crude oil is good. We construct a quarterly data series for world consumption of oil, simply because no such series was previously available.

² Because we have data from both sources for 2007:Q2, we can check the extent to which the series differ in this quarter. We find that the difference is very small, but we still use this difference (measured as a percentage) to adjust the [Kaufmann et al. \(2008\)](#) data.

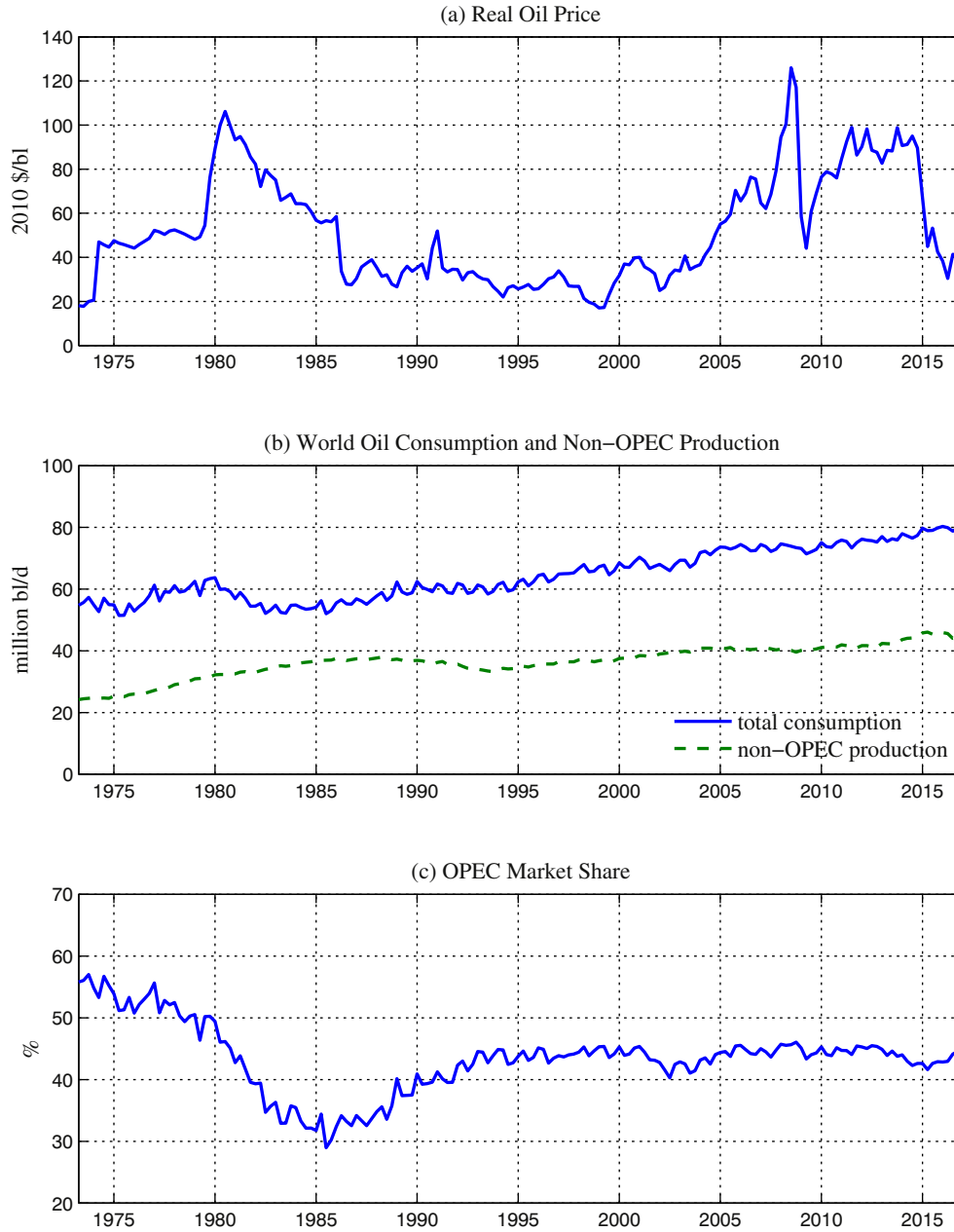


Fig. 1. Oil production and real price of oil (2010 USD).
 Notes: Panel (a) plots the real WTI price collected from Federal Reserve Bank of St. Louis (2017). Nominal prices are deflated by the US CPI from the U.S. Bureau of Labor Statistics (2017a). Panel (b) plots world oil consumption and non-OPEC production. World consumption is defined as the sum of world production and the drop in OECD inventory of oil. All quantity series are collected from EIA (2017). Panel (c) plots the OPEC market share.

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:

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

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

V^{no} contains other factors that may have an impact on non-OPEC supply of oil.

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 Eq. (2):

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

where

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

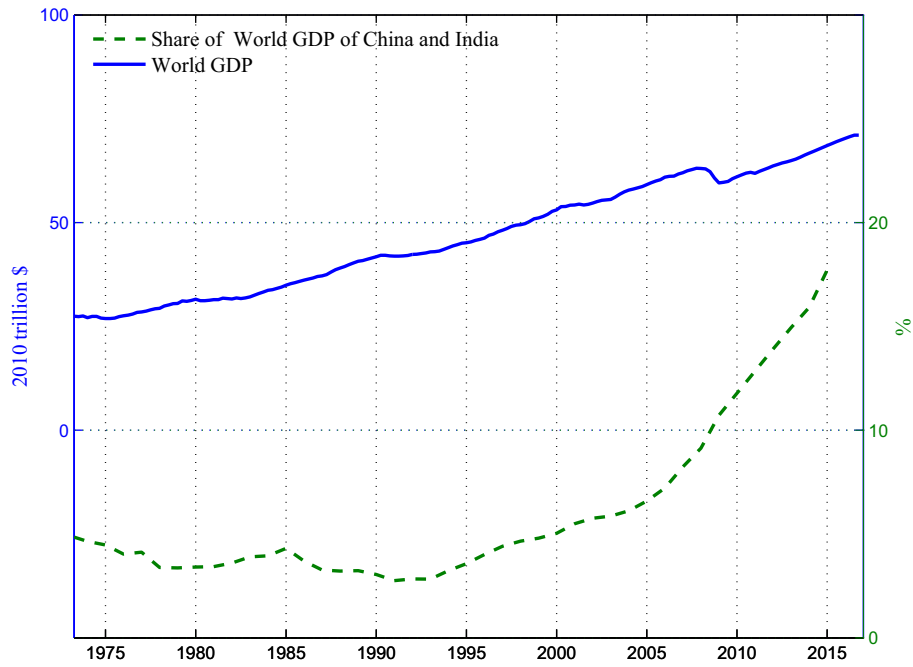


Fig. 2. Real world GDP and China and India's share of world GDP.

Notes: The figure plots real world GDP (measured by the left vertical axis in 2010 USD) and China and India's share of world GDP (measured by the right vertical axis). World GDP is combined using the GDP index from Fagan et al. (2001) for the period 1986–2010 and Global Financial Data (2017) for the period 2011–2016.

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, Eq. (2) can be rewritten

as $P(Q^o + Q^{no}) = MC^{no}(Q^{no}, W^{no}, V^{no})$, which implicitly defines the function $Q^{no} = Q^{no}(Q^o)$ where

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

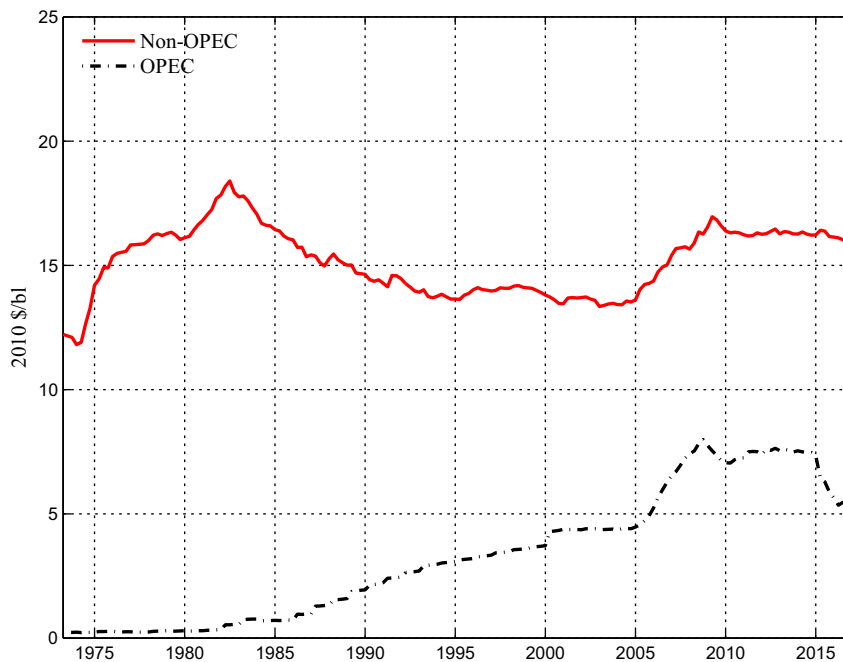


Fig. 3. Real cost of production in OPEC and non-OPEC.

Notes: The OPEC cost series is annual cost of OPEC for 1975–2000 in Hansen and Lindholt (2008) and quarterly observations of costs of exploration, development and production for 2001:Q1–2016:Q4 from IHS CERA. The source for the non-OPEC cost is U.S. Bureau of Labor Statistics (2017b). It is a Producer Price Index for oil and gas field machinery and equipment in the United States. We set the nominal cost for non-OPEC to 10 USD per barrel in 1999:Q2 (IHS CERA, 2000).

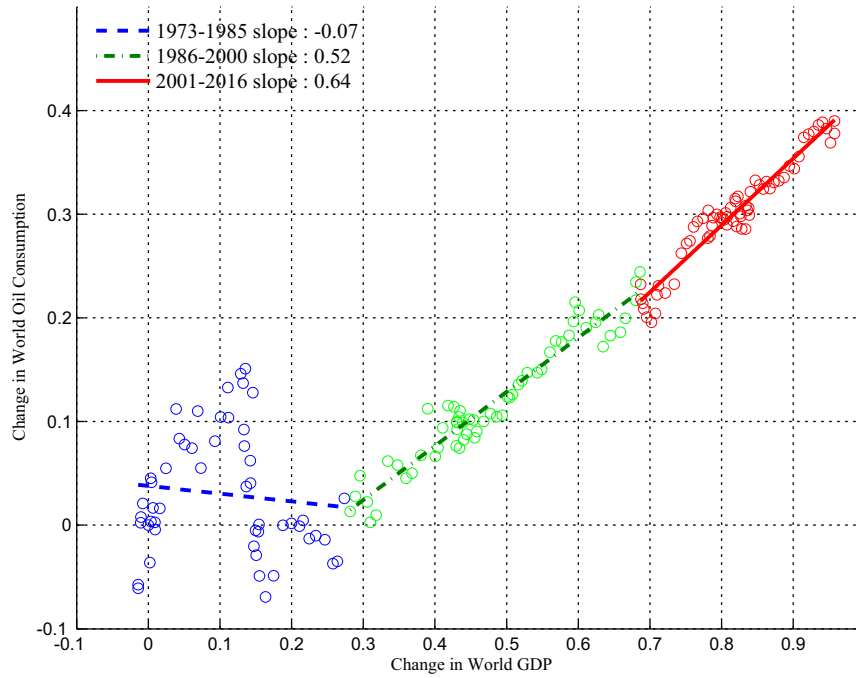


Fig. 4. Changes in real world GDP and world oil consumption.

Notes: The horizontal axis shows cumulative change in (natural logarithm of) real world GDP (measured in 2010 USD) for different periods, that is, $\sum_{s=1}^{s=t} (\ln Y_{s+1} - \ln Y_s)$ where $s = 1$ is the first quarter in the data period, for example, the first quarter in 1986, $s = 2$ is the second quarter in the data period, etc. For the subset of data covering 1973 to 1985, t is a quarter between the second quarter in 1973 and the fourth quarter in 1985. The vertical axis shows cumulative change in (natural logarithm of) total oil consumption Q^w . Each point in the figure represents a pair $\left\{ \sum_{s=1}^{s=t} (\ln Y_{s+1} - \ln Y_s), \sum_{s=1}^{s=t} (\ln Q_{s+1}^w - \ln Q_s^w) \right\}$. The slopes are estimated using OLS with a constant.

OPEC maximizes profits, taking Eq. (5) into account, that is, OPEC maximizes $P(Q^o + Q^{no})Q^o - c^o(Q^o, W^o, V^o)$ with respect to Q^o , where $c^o(Q^o, W^o, V^o)$ 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 states that price should be a markup over marginal cost,

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

where the markup m is defined as

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

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 $m(\epsilon, \gamma, s^o) = \left(1 + \frac{1}{\epsilon^o}\right)^{-1}$, 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 use later, is given by

$$P = MC^o(Q^o, W^o, V^o) - \lambda \frac{\partial P}{\partial Q^w} Q^o \tag{8}$$

where

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

Here, 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 such as Cournot competition and a dominant firm with a competitive fringe (our benchmark case).⁴

3.2. Empirical implementation

Our empirical goal is to estimate parameters for long-run elasticities for supply and demand. Under both market structures (dominant firm and competitive), we have a simultaneous system of equations that determines oil production in OPEC and non-OPEC countries, total oil production and the world price of oil.

⁴ As pointed out in Bresnahan (1982), if both demand and marginal cost are linear in quantity, then estimation of a relation of type Eq. (8) will identify the gross effect of increased 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 .

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

3.2.1. Specification

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

$$\ln Q_t^w = \alpha_0 + \alpha_1 \ln P_t + \alpha_2 \ln Y_t + \alpha_3 V_t^w + \alpha_4 D_t^w + u_t^w, \quad (10)$$

where t is time, D_t^i is a vector of dummies, $i = w, no, o$,⁵ and u_t^i is an error term assumed to be independent and identically distributed with zero mean and variance σ_i^2 . Further, $V_t^w = [\Delta \ln Y_t, \dots, \Delta \ln Y_{t-q}]$ is a vector of shifters. As suggested by Stock and Watson (1993), we augment our empirical model with a vector of lagged differences of independent variables and use dynamic OLS to obtain efficient statistical tests. 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 Eq. (2). Assuming that marginal cost is log-linear⁶, the supply of non-OPEC production is also log-linear:

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

where $V_t^{no} = [\Delta \ln W_t^{no}, \dots, \Delta \ln W_{t-q}^{no}]$ is a vector of shifters. Further, $\beta_1 = \gamma > 0$ and $\beta_2 < 0$ according to standard economic theory.

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

$$\ln Q_t^o = \pi_0^c + \pi_1^c \ln P_t + \pi_2^c \ln W_t^o + \pi_3^c V_t^o + \pi_4^c D_t^o + u_t^o, \quad (12)$$

where $V_t^o = [\Delta \ln W_t^o, \dots, \Delta \ln W_{t-q}^o, \text{cap}_t^o, \text{cap}_{t-1}^o, \Delta \ln \text{cap}_{t-2}^o, \dots, \Delta \ln \text{cap}_{t-q-1}^o]$ is a vector of shifters. Note that V_t^o also contains the capacity of OPEC (cap^o), both the level (lagged to account for the endogeneity of this factor) and lagged differences.

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

$$\ln P_t = \pi_0^d + \ln m(\alpha_1, \beta_1, s_t^o) + \pi_1^d \ln Q_t^o + \pi_2^d \ln W_t^o + \pi_3^d V_t^o + \pi_4^d D_t^o + u_t^o, \quad (13)$$

where

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

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

⁵ For the demand function Eq. (10), we use quarterly dummies (one dummy for each of the first three quarters). For the other relations, that is, Eqs. (11), (12) and (13), we use the same quarterly dummies as well as a dummy for wars in the Middle East and another dummy for the former Soviet Union. 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 (1990:Q3–Q4). The former Soviet Union dummy equals 1 for the period, 1986:Q1–1990:Q2, reflecting the contraction of the Soviet energy industry in this period.

⁶ Implicitly, we allow for a nonhomothetic cost function in factor prices and output. Constant returns-to-scale technology would imply independence of the marginal cost with respect to production.

to be estimated – this is explored in more detail in the next subsection.

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

$$\lambda_t = \frac{\alpha_1}{\alpha_1 - \beta_1(1 - s_t^o)} > 0. \quad (14)$$

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

3.2.2. Estimation methods

In this subsection, 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 Eqs. (10), (11) and (12), where $\alpha = [\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4]$, $\beta = [\beta_0, \beta_1, \beta_2, \beta_3, \beta_4]$ and $\pi^c = [\pi_0^c, \pi_1^c, \pi_2^c, \pi_3^c, \pi_4^c]$. Then, for the dominant firm specification, where OPEC charges a markup over marginal cost, we estimate the parameters $\theta^d = [\alpha, \beta, \pi^d]$ using Eqs. (10), (11) and (13), where $\pi^d = [\pi_0^d, \pi_1^d, \pi_2^d, \pi_3^d, \pi_4^d]$. In both cases, the vector of instrument variables is

$$Z_t = [\ln Y_t, \ln W_t^{no}, \ln W_t^o, \ln V_t^w, \ln V_t^{no}, \ln V_t^o], \quad (15)$$

and we use the same number of lags in both the dominant firm model and the competitive model ($q = 3$); see Section 5 for a discussion on the importance of lags with respect to the empirical results. When estimating the competitive model, we use the three-stage least-squares (3SLS) method. In contrast, we use system nonlinear instrumental variable (NLIV) method when estimating the dominant firm model, see Appendix A for details.

4. Results

In this section, we present our main results. First, we present 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 1986–2016 period.

4.1. Elasticities

The second column in Table 1 shows our estimates for the dominant firm model – Eqs. (10), (11) and (13) – using the NLIV method. The third column in Table 1 shows the estimates from the competitive model – Eqs. (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 an overidentification test for the instruments Z_t , see Eq. (15), for the dominant firm model. To test for the validity of the instruments, that is, the exogeneity of these variables, we use the Sargan-Hansen J -statistic, which equals the value of the GMM objective function evaluated at the estimated parameters. We find that the value of the J -statistic is 1.28. The critical value of the chi-square distribution with 31 degrees of freedom is 29.34 at the 5% significance level. Hence, we cannot reject the null hypothesis that the instruments are exogenous to our system of simultaneous equations.

Table 1
Estimates for the dominant firm and the competitive models.

Models	Dominant firm		Competitive	
	NLIV		3SLS	
<i>World demand</i>				
$\frac{\partial \ln Q^w}{\partial \ln P}$ α_1		-0.352(0.018)		0.003(0.004)
$\frac{\partial \ln Q^w}{\partial \ln Y}$ α_2		1.154(0.117)		0.543(0.010)
<i>Non-OPEC supply</i>				
$\frac{\partial \ln Q^{no}}{\partial \ln P}$ β_1		0.322(0.034)		0.076(0.018)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$ β_2		-0.758(0.372)		0.392(0.107)
<i>OPEC supply</i>				
$\frac{\partial \ln MC^o}{\partial \ln P}$ π_1^d	1.545(0.904)	$\frac{\partial \ln Q^o}{\partial \ln P}$	π_1^c	0.194(0.083)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$ π_2^d	1.516(0.247)	$\frac{\partial \ln Q^o}{\partial \ln W^o}$	π_2^c	-0.183(0.157)
λ	0.655(0.035)			
<i>Overidentification test $J \sim \chi^2(dof)$</i>				
J-statistic	1.281			1.437
Degrees of freedom	31			31

Notes: We use quarterly data for the period 1986:Q1–2016: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, Eqs. (10), (11) and (13), using a nonlinear instrumental variable (NLIV) method. The third column shows the estimates for the competitive model, that is, Eqs. (10), (11) and (12), using three-stage least-squares (3SLS) estimation. The predetermined exogenous variables used in the models are $V_t^w = \Delta \ln Y_t, \dots, \Delta \ln Y_{t-q}$ in the demand equation, $V_t^{no} = \Delta \ln W_t^{no}, \dots, \Delta \ln W_{t-q}^{no}$ in the non-OPEC supply equation and $V_t^o = [\Delta \ln W_t^o, \dots, \Delta \ln W_{t-q}^o, cap_{t-1}^o, \Delta \ln cap_{t-2}^o, \dots, \Delta \ln cap_{t-q-1}^o]$ in the OPEC equation, all with $q = 3$. 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 the 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 39 degrees of freedom at the 5% significance level is 54.572.

4.1.1. OPEC as the dominant firm

4.1.1.1. Price elasticity of oil demand. The crude oil demand elasticity is estimated to be -0.35 (with standard error of 0.02).⁷ 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 Cooper (2003), Dahl and Yücel (1991), Gately and Huntington (2002) and 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) estimate a single demand equation for the 1971–1997 period, allowing the demand response to a price increase to differ from the demand response to a price decrease. In their most preferred empirical specification, the long-run price elasticity for oil consumption per capita (due to a price increase) was estimated to be -0.64 for the group of OECD countries and -0.18 for non-OECD countries. Among non-OECD countries with a steady growth in per-capita income, the long-run price elasticity was estimated to be -0.12.

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 Eq. (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 (-0.35) reflects i) different

data, and ii) a 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 1986–2016 like we do) and their data for cost of production for OPEC and non-OPEC differs from what we use. 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 0.01 (0.00), whereas we obtain 0.00 (0.00) with IV (when the same instruments as in the benchmark case are used). These results clearly show the importance of specifying the market structure.

4.1.1.2. Income elasticity. We obtain an income elasticity of 1.15 (the standard error is 0.12). 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) also estimate income elasticities for the 1971–1997 period. Similar to the price elasticity, they allow for asymmetric responses to a change in income, that is, the income elasticity related to a rise in income might differ from the one associated with a decrease in income. They estimate the income elasticity (in the case of higher income) to 0.56 for the group of OECD countries, as opposed to 0.53 for the group of non-OECD countries. For non-OECD countries with a steady growth in per-capita income, the long-run income elasticity was estimated to 0.95. The reasons we obtain a higher estimate of the income elasticity than other studies could be because i) we estimate a simultaneous structural model; ii) our specification of the demand function may differ from other studies, for example, with respect to lag structure (see the discussion in Section 5); and iii) our data period differs from the others.

4.1.1.3. Non-OPEC supply. For non-OPEC producers, we obtain a supply elasticity of 0.32 (the standard error is 0.03), meaning that a 1% increase in the crude oil price will increase extraction from the non-OPEC producers by 0.32%. 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 -0.76 (the standard error is 0.39) that is, a 1% increase in the unit cost of extraction leads to a slightly smaller reduction in non-OPEC production.

4.1.1.4. OPEC price-setting equation. We estimate a marginal cost elasticity for OPEC ($\frac{\partial \ln MC^o}{\partial \ln Q^o}$) of 1.55; this estimate is insignificant at the 5% level of significance (the standard error is 0.90), but significant at the 10% level. We can examine whether the marginal cost elasticities of OPEC and non-OPEC differ: a simple one-sided t-test suggests that at the 5% significance level, the marginal cost elasticity is larger for non-OPEC than for OPEC. This could be due to competitive advantages because reserves are more accessible and cheaper to exploit in OPEC than in non-OPEC countries.

The imprecise estimate of the marginal cost elasticity of OPEC may reflect omitted explanatory variables or poor data. For example, although the data on OPEC cost of production cover exploration, extraction and production, they may not adequately reflect the geology of the oil fields, such as the costs of new fields relative to the costs of fields under extraction. Alternatively, the insignificant marginal cost elasticity may reflect a serious misspecification because the model 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. Such a signal may trigger a change in the non-OPEC extraction path, which may cause a response by OPEC.

⁷ The standard errors are the Newey-West standard errors, which correct for heteroskedasticity and serial correlation in the coefficient covariance matrix. In the estimation, we employ three lags to estimate the Newey-West standard errors.

The OPEC factor price elasticity $\left(\frac{\partial \ln MC^o}{\partial \ln W^o}\right)$ is estimated to 1.52 (the standard error is 0.25). If OPEC production increases, then, *ceteris paribus*, the market price will fall, which would lower non-OPEC production, thereby, modifying the initial price reduction. We call this the *equilibrium* elasticity of OPEC production $\left(\frac{\partial \ln P}{\partial \ln Q^o}\right)$, and it is straightforward to identify it in our framework: our estimate is -0.79 (the standard error is 0.05).⁸ The estimate of the market power index λ is 0.66, which is clearly above zero. Moreover, the market power index estimate is sharply estimated – its standard error is only 0.04.⁹ These results suggest that OPEC exerts market power; we return to this issue in Section 4.3.

Finally, using our estimated parameters, we find that OPEC's markup, see Eq. (7), varies between 2.3 and 8.1 with a mean of 5.3, that is, far above one.¹⁰

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 OPEC's level of production, see Eq. (5). The competitive model is estimated using 3SLS.

4.1.2.1. Demand. As seen from the last column in Table 1, the demand elasticity has the wrong sign, but it is small and insignificant; 0.003 (0.004) versus -0.35 (0.02) in the benchmark case.¹¹ In the competitive model, the estimated income elasticity is 0.54 (0.01), which is much smaller than the 1.15 estimate in the benchmark case. This suggests that not accounting for the non-competitive market structure in the specification of the econometric model leads to biases in the estimates of the demand and income elasticities.

4.1.2.2. Non-OPEC supply. The supply elasticity of non-OPEC is estimated to 0.08 (0.02), which is smaller than in the dominant firm model (0.32). The factor price elasticity of non-OPEC is alarming; it has the wrong sign (0.39) and the estimate is significant (the standard error is 0.11).

4.1.2.3. OPEC supply. When OPEC is assumed to act competitively, its estimated supply elasticity is 0.19 (0.08), which is small but somewhat higher than the supply elasticity of non-OPEC (0.08). 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 empirical relevance of the competitive oil price model. In the remaining part of the paper, we, therefore, focus on the dominant firm model.

⁸ Notice that

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

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 $e^o = -\frac{1}{0.76} < -1$ at equilibrium.

⁹ 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.

¹⁰ Recall that in our estimation, we have imposed that the markup is strictly positive. Our point estimates clearly meet this restriction.

¹¹ 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 the two-stage least-square method to estimate short-run elasticities, and error-correction methods 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; namely, no price effect on demand.

4.2. Fit of the dominant firm model

Using the estimated parameters of the dominant firm model, we evaluate the fit of the model using the exogenous variables for the 1986–2016 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.

4.2.1. In-sample prediction

Fig. 5 shows the in-sample prediction of the dominant firm model. In general, the model tracks the main trends in the market reasonably well, but understandably misses some deviations from the trend.

- The dominant firm model is able to predict the decline in world oil consumption in 2009, as well as the recovery from 2010.
- The model also has some success in predicting the trend in non-OPEC supply. In particular, it predicts an increase in non-OPEC supply after 2012. This event coincides with an increase in extraction of light tight oil in the United States.
- However, the model does not capture abrupt changes in the oil price, for example, the sudden fall in 2014. The model is built to capture long-run trends, and, therefore, will have trouble predicting short-term dynamics.

We now examine which exogenous factor – world GDP or cost of oil production – that contributes most to the trends in oil consumption, non-OPEC supply, and the oil price predicted by the benchmark model.¹² Each panel in Fig. 6 shows three curves. The solid curves are the predicted paths of quantities and prices, obtained by 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 cost of oil production 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 Fig. 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 2005. 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 2016 would have been roughly 15% above the 1997 price, whereas the predicted 2016 oil price when world GDP is *not* kept constant is roughly 120% above the 1997 price, see panel (c) in Fig. 6. Finally, from panels (b) and (c), we see that cost of oil production has contributed to a higher oil price in the last six years.

To summarize, the path of world GDP explains most of the increase in the oil price between 1986 and 2016. Increased cost of production has, however, contributed to the increase in the oil price during the last six years. Note that a similar conclusion was found in Smith (2009), who also examined the importance of demand and supply factors for the long-run behavior of the oil price, albeit using a somewhat different method than we do.

¹² There are clear limitations of the present analysis because we use a partial equilibrium framework. First, GDP and cost of oil production are likely to be dependent on each other. In addition, GDP may be affected by the price of oil, for example, as modeled by Hassler et al. (2012).

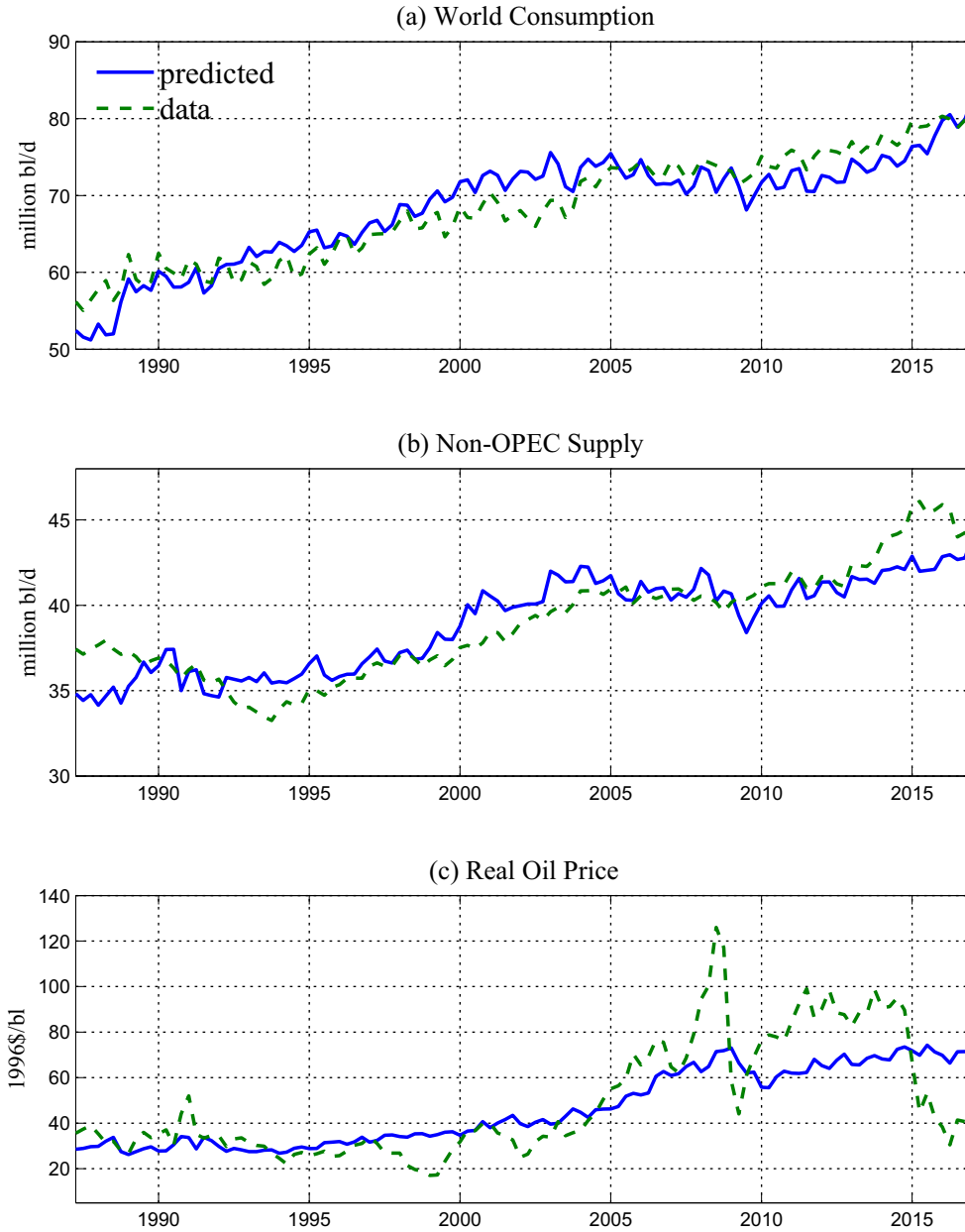


Fig. 5. In-sample prediction for the dominant firm model. Notes: Panels (a)–(c) plot the in-sample prediction of world consumption, non-OPEC supply, and the real oil price (1996 USD) for the dominant firm model.

4.3. OPEC's market power

We have documented that OPEC's market power index is high – the estimate of λ is 0.66 at the mean value of the market share (the standard error is 0.04), see Table 1. This clearly suggests that OPEC has market power. A simple approach to assess the market power of OPEC is to calculate the standard Lerner index L_t . Using Eq. (8), we find

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

The Lerner index had a positive trend between 1986 (61%) and 1998 (86%). This trend is entirely driven by changes in OPEC's market share because, in our model, the elasticities are constant. Note

that $L_t = \frac{1}{-\epsilon} = -\frac{\partial \ln P}{\partial \ln Q^o}$, that is, the absolute value of the OPEC production elasticity increased over time in this period. After 1998, the Lerner index varied between 74% and 88%. For the entire 1986–2016 period, the average Lerner index was 79%.

Is it possible to test whether OPEC has market power? Here, there is a fundamental problem because the dominant firm 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 Eq. (5). Hence, $\lambda = 0$ is not defined in our dominant firm model.

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 the 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

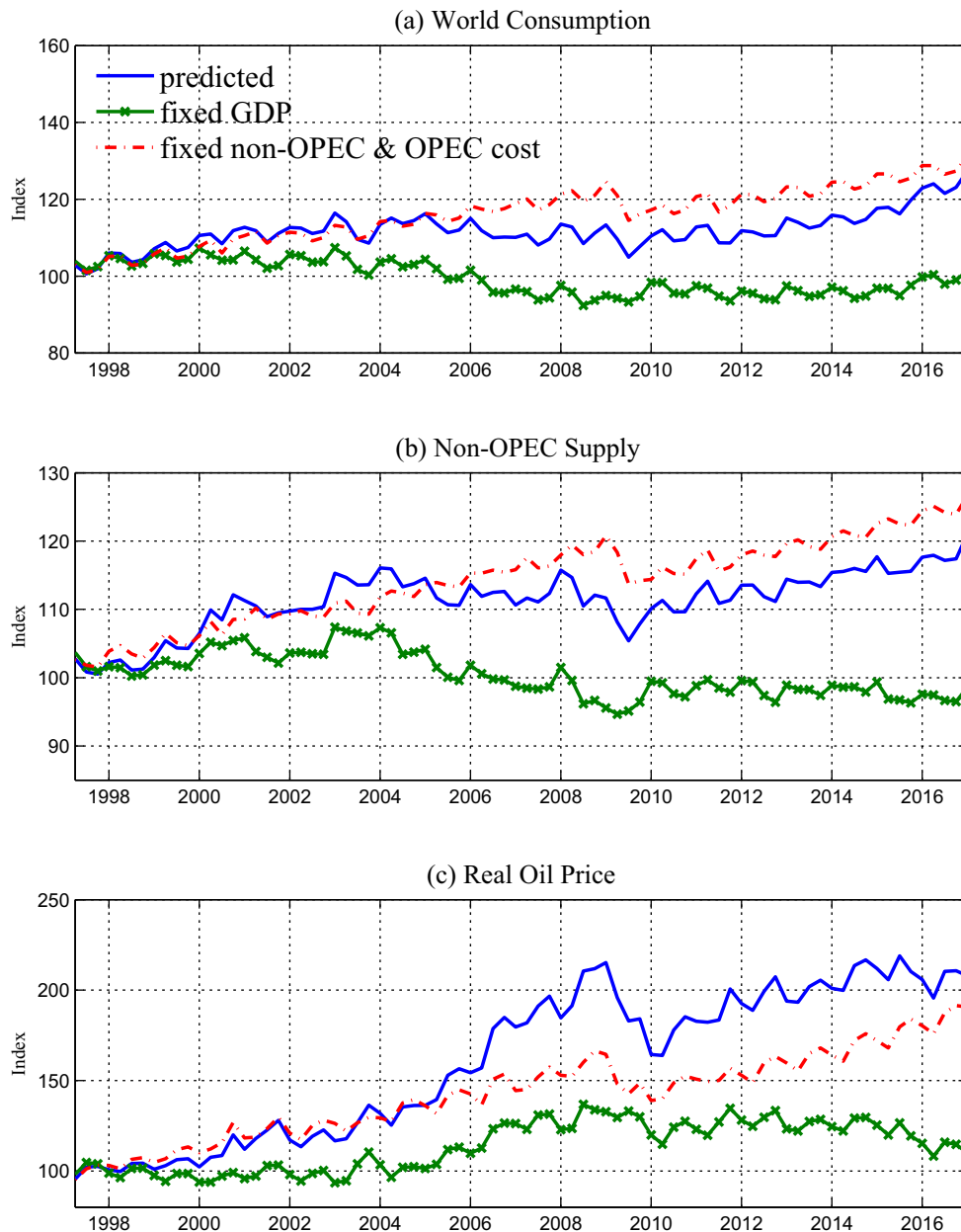


Fig. 6. In-sample prediction for the dominant firm model with constant GDP or constant cost of oil production.

Notes: Panels (a)–(c) show the in-sample prediction for world consumption, non-OPEC supply, and the real oil price (2010 USD) for the dominant firm 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. The figure plots the bootstrap 99th percent confidence intervals using percentiles from the empirical sampling distribution of the market power index $\hat{\lambda}$. We use a resampling 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.

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 , $j = 1, \dots, 10,000$, 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 Eq. (14) to compute $\hat{\lambda}_j^*$ (* denotes the estimate from the bootstrap process); see Appendix B for more details. The set of all $\hat{\lambda}_j^*$ is the empirical distribution of $\hat{\lambda}$. Finally, we construct the 99th percentile confidence interval (one for each year) using the bootstrap sampling distribution of $\hat{\lambda}$. Fig. 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 99th percentile confidence intervals are well above zero.

To test whether OPEC has market power, we compare our benchmark dominant firm model with the alternative competitive model. To this end, we use the non-nested statistical test of Smith (1992) for competing models that are estimated by the generalized method of moments, see Appendix C. Here, we find that there is no evidence to reject the dominant firm model against the competitive model. In addition, we find strong evidence in favor of rejecting the competitive model against the dominant firm model. These results

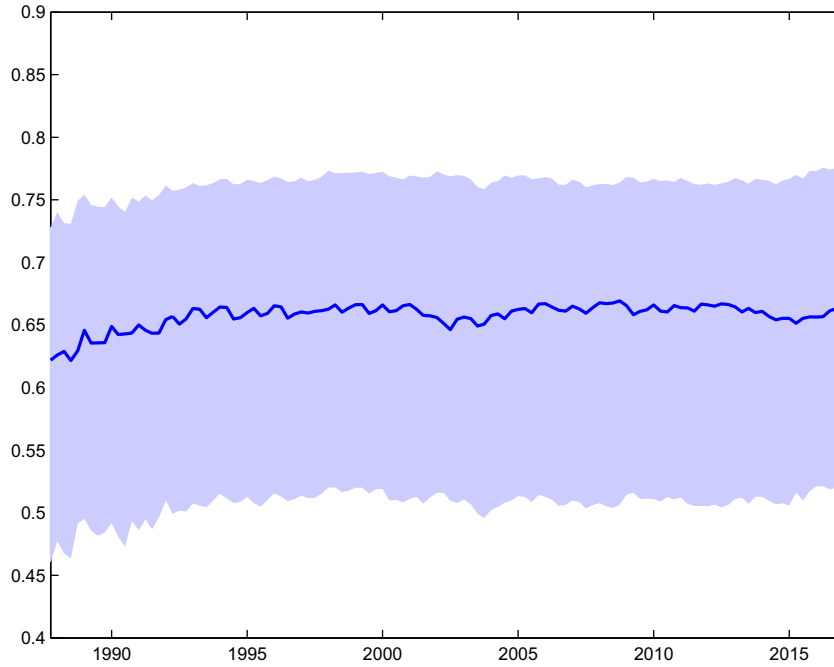


Fig. 7. Bootstrap 99th percent confidence intervals of the market power index.

Notes: The figure plots the bootstrap 99th percent confidence intervals using percentiles from the empirical sampling distribution of the market power index $\hat{\lambda}$. We use a resampling 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.

lend support to the dominant firm model, and, thus, that OPEC exerted market power in the period, 1986–2016.

5. Further analysis

We now examine how different econometric specifications and data may change our estimates. First, we explore the robustness of our estimates when we allow for different numbers of lags. Second, we investigate how the estimates vary between subperiods. This may shed light on parameter shifts due to structural changes in demand and supply. Third, we study the impact of using the consumer price of oil instead of the producer price of oil in the demand function. Fourth, we check whether the estimates change when we use alternative

cost data for the non-OPEC countries or an alternative definition of OPEC membership. Finally, we assume that only a few OPEC countries – OPEC core – exert market power, whereas all other OPEC members are de facto price takers.

5.1. Lags

It is standard to include lags in oil market studies; for example, Hansen and Lindholt (2008) 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 the number of lags.

In the benchmark case, we used three lags. Table 2 shows that the estimated coefficients for demand, non-OPEC supply and the

Table 2
Estimates using different numbers of lags: the dominant firm model.

No.lags		0 lag	3 lags	8 lags	12 lags
q		Static	Benchmark		
<i>World demand</i>					
$\frac{\partial \ln Q^w}{\partial \ln P}$	α_1	-0.295(0.019)	-0.352(0.018)	-0.350(0.018)	-0.367(0.020)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	α_2	1.040(0.082)	1.154(0.117)	1.197(0.128)	1.243(0.150)
<i>Non-OPEC supply</i>					
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	β_1	0.325(0.036)	0.322(0.034)	0.300(0.032)	0.293(0.036)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	β_2	-0.797(0.361)	-0.758(0.372)	-0.579(0.363)	-0.543(0.375)
<i>OPEC supply</i>					
$\frac{\partial \ln M^o}{\partial \ln Q^o}$	π_1^d	7.681(16.009)	1.545(0.904)	0.063(0.855)	-1.264(0.740)
$\frac{\partial \ln M^o}{\partial \ln W^o}$	π_2^d	0.424(3.291)	1.516(0.247)	1.749(0.228)	1.944(0.225)
λ		0.613(0.041)	0.655(0.035)	0.670(0.035)	0.686(0.038)

Notes: We use quarterly data for the period 1986:Q1–2016: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 different numbers of lags for the lagged differences of (log of) the exogenous variables V_t^w, V_t^{no} and V_t^o in Eqs. (10), (11) and (13).

market power index are robust with respect to the number of lags. For example, the estimate of the demand elasticity varies between -0.30 (no lag) and -0.37 (12 lags), and the non-OPEC supply elasticity varies between 0.33 (no lag) and 0.29 (12 lags). On the other hand, the estimated OPEC parameters are sensitive to the lag specification. For example, the OPEC factor price elasticity varies between 7.68 (no lag) and 0.06 (8 lags), and the marginal cost elasticity of OPEC becomes negative with 12 lags. (This elasticity is not significantly different from zero for any lag specification, except the benchmark case.) The lack of stability may be due to no dynamic behavior in the model; see the discussion above.

5.2. Data period

In our estimations, we assumed constant parameter values over the data period, 1986:Q1–2016: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 several studies, has a lower demand elasticity than other oil-consuming sectors, such as the manufacturing industry 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 related to Fig. 2. The energy and environmental policy in OECD countries, and also discoveries of unconventional petroleum deposits in non-OPEC countries, may have a powerful impact on OPEC's ability to act as a profit-maximizing cartel, and, thus, on total OPEC production.

To investigate the variation in the parameters across periods, we divide the data period into two subperiods, 1986–2000 and 2001–2016, 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 -0.38) and they are close to the benchmark estimate (-0.35). On the other hand, for the income elasticity, the difference in the subperiod estimates is large; 0.18 (1986–2002) versus 1.23 (2001–2016). The 2001–2016 estimate probably mirrors the rapid growth of China and India in this period.

For non-OPEC, the supply elasticity is robust with respect to the estimation period, whereas the factor price elasticity is either insignificant (1986–2000) or has the wrong sign (2001–2016). For OPEC, the factor price elasticity is robust with respect to the sample period, whereas the marginal cost elasticity is insignificant (and has

the wrong sign) in each subperiod. The latter result indicates that the model is too simple to represent the dynamics of the oil market, at least within a period of 15 years.

5.3. The consumer price of oil

In our 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 in OECD countries typically face a 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.). However, in several non-OECD countries, oil products are subsidized. In this subsection, we first construct a global consumer price for oil products, and then estimate the model using this consumer price as the explanatory variable in the demand function. By using the consumer price of oil products as an explanatory variable, our estimated demand elasticity becomes comparable to demand elasticities that are obtained from other econometric studies.

To calculate a global end-user price of oil, we use data from Energy Prices and Taxes and Energy Balances of non-OECD countries (which also contain OECD data) from the IEA. Because Energy Prices and Taxes has not published detailed end-user prices for oil products after 2010, our series for the consumer price covers the period 1996–2010. Finally, the consumer price data are annual, and we, therefore, transform this series into a quarterly series. To this end, we assume that in each year, the quarterly changes in the consumer price are identical to the quarterly changes in the crude oil price.

Table 4 shows the estimates when we use the world consumer price of oil (instead of the crude oil price – PPI) as the explanatory variable in the demand function. For some elasticities, the change is small; the demand elasticity is now -0.24 (-0.35 if we use the PPI as the explanatory variable in the demand function), whereas, for other parameters, the change is larger; the non-OPEC supply elasticity is 0.53 (0.36 if we use the PPI), and the market power index is 0.44 (0.63 if we use the PPI). To sum up, overall the estimates are moderately affected by using the global consumer price of oil products in the demand function (instead of the crude oil price).

5.4. Alternative cost data for non-OPEC

In the benchmark estimation, we used the US PPI index for oil and gas field machinery and equipment costs as a proxy for cost

Table 3
Estimates for different time periods: the dominant firm model.

Periods		1986–2016	1986–2000	2001–2016
Benchmark				
<i>World demand</i>				
$\frac{\partial \ln Q^w}{\partial \ln P}$	α_1	$-0.352(0.018)$	$-0.422(0.046)$	$-0.379(0.022)$
$\frac{\partial \ln Q^w}{\partial \ln Y}$	α_2	$1.154(0.117)$	$0.181(0.256)$	$1.228(0.656)$
<i>Non-OPEC supply</i>				
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	β_1	$0.322(0.034)$	$0.238(0.091)$	$0.271(0.040)$
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	β_2	$-0.758(0.372)$	$0.123(0.692)$	$-0.558(0.269)$
<i>OPEC supply</i>				
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	π_1^d	$1.545(0.904)$	$-0.523(1.296)$	$-0.561(0.987)$
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	π_2^d	$1.516(0.247)$	$1.402(0.685)$	$1.413(0.451)$
λ		$0.655(0.035)$	$0.751(0.091)$	$0.714(0.041)$

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 – Eqs. (10), (11) and (13).

Table 4
Estimates using the consumer price of oil: the dominant firm model.

Prices		Crude oil price	Consumer price
		1986–2010	1986–2010
<i>World demand</i>			
$\frac{\partial \ln Q^w}{\partial \ln P}$	α_1	$-0.352(0.022)$	$-0.239(0.033)$
$\frac{\partial \ln Q^w}{\partial \ln Y}$	α_2	$1.119(0.149)$	$1.181(0.173)$
<i>Non-OPEC supply</i>			
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	β_1	$0.357(0.040)$	$0.530(0.055)$
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	β_2	$-1.237(0.340)$	$-2.024(0.498)$
<i>OPEC supply</i>			
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	π_1^d	$1.932(1.015)$	$1.860(1.084)$
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	π_2^d	$1.373(0.266)$	$1.356(0.274)$
λ		$0.631(0.040)$	$0.438(0.049)$

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 and the market power index λ for the dominant firm model using either the crude oil price or the world consumer price as an explanatory variable for demand for oil.

Table 5
Estimates using alternative non-OPEC cost data: the dominant firm model.

Prices	PPI		Oil equipment cost
	1986–2016 benchmark		1986–2009
<i>World demand</i>			
$\frac{\partial \ln Q^w}{\partial \ln P}$	α_1	-0.352(0.022)	-0.367(0.020)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	α_2	1.119(0.149)	1.077(0.161)
<i>Non-OPEC supply</i>			
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	β_1	0.357(0.040)	0.344(0.035)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	β_2	-1.237(0.340)	-1.175(0.402)
<i>OPEC supply</i>			
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	π_1^d	1.932(1.015)	1.857(1.049)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	π_2^d	1.373(0.266)	1.332(0.261)
λ		0.631(0.040)	0.648(0.034)

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 and the market power index λ for the dominant firm model using either the PPI oil and gas field machinery and equipment or the oil lease equipment cost for non-OPEC cost of production in the periods 1986–2016 and 1986–2009.

of production for the non-OPEC countries. We used this quarterly series because it is available for the whole sample period. The PPI has three major weaknesses. First, while economic theory suggests to use data for *marginal* cost, the PPI measures *average* cost. Second, the PPI is constructed for the US industry, and, hence, it does not cover other countries. Needless to say, costs may vary significantly between non-OPEC countries. Ideally, we would like to use country-specific indices. Third, the PPI may not capture important shifts in the cost structure of non-OPEC producers. To explore the sensitivity of the cost data, we reestimate our model using the US oil lease equipment cost from EIA (2010), which is available for the period 1986–2009. This annual series is transformed into a quarterly series, assuming that, in each year, it has the same quarterly pattern as the PPI.

Note that the cost data in EIA (2010) indicate that the US PPI index has underestimated the increase in average cost of producing oil in the period 2003–2009. According to the EIA report, fluctuations in US oil production equipment costs in 2003–2009 are mainly due to an increase in steel prices, reflecting increased demand from China.

The empirical results are shown in Table 5. The first column shows the benchmark. Here, the PPI is used for non-OPEC cost and the sample period is 1986–2016. The second column shows the estimates when the sample period is 1986–2009 and the PPI is (still) used for non-OPEC cost. Hence, the difference between columns 1 and 2 is the effect of reducing the sample period from 2016 to 2009; this has a negligible effect on most estimates. The last column shows the estimates when the data from EIA (2010) are used for the cost of non-OPEC, and the sample period is 1986–2009. Thus, by comparing columns 2 and 3, we identify the partial effect of replacing the PPI with data from EIA (2010). As seen from Table 5, the price elasticity of demand drops from 0.37 (column 2) to 0.21 (column 3), and the non-OPEC supply elasticity increases from 0.34 to 0.67. These changes imply a lower market power index when the data from EIA (2010) are used; 0.65 vs. 0.35. On the other hand, using 95% confidence intervals, we find that the income elasticity and also the non-OPEC cost elasticity do not differ significantly between the two cases.

5.5. The role of entry and exit from OPEC

In our benchmark, OPEC membership is taken from the EIA database. Here, a country being a member of OPEC in the most current year is considered an OPEC member in *all* previous years.

Table 6
Estimates using alternative definitions of OPEC: the dominant firm model.

Def. of OPEC	OPEC original		OPEC with entry & exit
	Benchmark		
<i>World demand</i>			
$\frac{\partial \ln Q^w}{\partial \ln P}$	α_1	-0.352(0.018)	-0.344(0.021)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	α_2	1.154(0.117)	1.140(0.116)
<i>Non-OPEC supply</i>			
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	β_1	0.322(0.034)	0.326(0.036)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	β_2	-0.758(0.372)	-0.864(0.364)
<i>OPEC supply</i>			
$\frac{\partial \ln MC^o}{\partial \ln Q^o}$	π_1^d	1.545(0.904)	0.805(1.217)
$\frac{\partial \ln MC^o}{\partial \ln W^o}$	π_2^d	1.516(0.247)	1.410(0.326)
λ		0.655(0.035)	0.642(0.038)

Notes: We use quarterly data for the period 1986:Q1–2016: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 two alternative definitions of OPEC membership: 1) current status, see EIA (2017); and 2) adjustment for entry and exit, see OPEC (2017).

In our benchmark, OPEC members are, therefore, Algeria, Angola, Ecuador, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates (UAE) and Venezuela (in all years in the period 1986–2016).

Needless to say, over time, some countries enter or exit the group of OPEC.¹³ To identify the robustness of our estimates with respect to the definition of OPEC, we have reestimated the model, requiring that, in each year, OPEC consists of those countries that were actually members in that year, see OPEC (2017). We find that demand and non-OPEC parameters are robust to the data adjustment, see Table 6. Hence, the estimate of the market power index hardly changes. For OPEC, the estimate of how higher cost impacts marginal cost is almost unchanged, whereas the estimate of how increased oil extraction impacts marginal cost is decreased.

5.6. OPEC core

So far, we have assumed that OPEC is a coordinated group facing a competitive fringe. However, several papers have pointed out that OPEC countries are heterogeneous and should be analyzed accordingly. Mabro (1998), reviewing the OPEC literature, emphasizes events where the behaviors of OPEC countries have varied. For example, the oil price increase in 1973 was induced by some Arab countries, whereas both Arab Iraq and non-Arab Iran did not join the embargo. The Iraq–Kuwait war caused only a short-run price increase because a few OPEC countries, in particular, Saudi Arabia and UAE, increased their supply to counteract lower production from Iraq and Kuwait.¹⁴

To explain asymmetric OPEC behavior, Hnyilicza and Pindyck (1976) suggest dividing OPEC countries into two groups – savers and spenders – whereas Eckbo (1976) distinguishes between the price pushers, the expansion fringe, and core OPEC members, the latter group consisting of Saudi Arabia and Kuwait, as well as some other countries. Brémond et al. (2012) use the grouping of Hnyilicza and Pindyck (1976) and conclude that, at least the group of savers, acts as a cartel. Griffin (1985) tests Eckbo’s grouping, and concludes that countries within each group do not have similar behavior, but still he

¹³ According to OPEC (2017), Angola joined OPEC in 2007; Gabon terminated its membership in 1995, but rejoined in 2016; Ecuador was suspended in 1992, but rejoined in 2007; and Indonesia was suspended in 2009, but rejoined in 2016.

¹⁴ For a study on Saudi Arabia’s behavior within OPEC, see Alkhatlan et al. (2014). They conclude that the primary goal of Saudi Arabia is to stabilize OPEC production.

prefers Eckbo's grouping rather than treating OPEC as a monolithic unit. Alhajji and Huettner (2000) estimate a dominant firm model (with the caveats explained above) and conclude that the behavior of the OPEC core countries is not consistent with the dominant firm model. However, Hansen and Lindholt (2008) find evidence that OPEC core countries have acted as a dominant firm after 1994. For comparison with other papers, we now estimate the dominant firm model for the OPEC core countries (Saudi Arabia, Kuwait, Qatar and UAE), assuming that all other oil-producing countries belong to the fringe. Below, this case is referred to as OPEC core.

In Section 2, we explained that we do not have country-specific cost data, only cost of production for an OPEC country and cost of production for a non-OPEC country (both vary over time). We, therefore, assume that cost of production of the new fringe consists of a weighted average of cost of production of a non-OPEC country and cost of production of an (original) OPEC country, with weights equal to the production share of the non-OPEC countries and the production share of the non-core OPEC countries (these shares add up to one).

Table 7 shows the results.¹⁵ For the demand elasticity, the estimate from the OPEC core model with three lags (−0.11) is clearly lower than for the benchmark case (−0.35). Also, the income elasticity and the non-OPEC supply elasticity are lower in the OPEC core model than in the benchmark case. Lower demand and supply elasticities tend to reduce the market power index, see Eq. (14), but, on the other hand, a lower OPEC market share (reflecting fewer OPEC producers) has the opposite effect. As seen from Table 7, the first effect dominates; the market index in the benchmark case (0.66) is almost twice as high as in the OPEC core model (0.35).

To understand why the estimates of the OPEC core model differ from the benchmark estimates, we note that, in the benchmark case, all OPEC members belong to the dominant firm, whereas, in the OPEC core model, the dominant firm consists of four OPEC countries only. Hence, a number of oil-producing countries have changed strategic position from taking into account the response of the fringe to being part of the fringe. This means that, if the dominant firm reduces the oil price, there will be a larger (quantity) response from the fringe in the OPEC core model than in the benchmark case, simply because the fringe is larger in the OPEC core model. For the same reason, the choke price of the residual demand curve is lower in the OPEC core model than in the benchmark case. If, hypothetically, the choke price in the benchmark case is charged by the dominant firm in the OPEC core model, then supply from the fringe would exceed demand. Hence, the residual demand curve shifts downwards (lower choke price) and becomes more price elastic (larger response from the fringe) if the market structure changes to the OPEC core. Standard economic theory then suggests that the degree of market power declines, which is in accordance with our finding.

Table 7 also provides information on whether the estimates are sensitive to the number of lags. When increasing the number of lags from three to eight, most estimates hardly change. This is similar to the results obtained for the benchmark model, see the discussion related to Table 2.

We also provide some information on the sensitivity of the results with respect to the sample period and the price variable in the demand function.¹⁶ For the subperiod, 1986–2000, the demand elasticity is −0.26 (compared with −0.11 for the period 1986–2016),

Table 7
Estimates for OPEC and OPEC core as the dominant firm.

Dominant firm	OPEC original definition		OPEC core	OPEC core
	3 lags		3 lags	8 lags
Benchmark				
<i>World demand</i>				
$\frac{\partial \ln Q^w}{\partial \ln P}$	α_1	−0.352(0.018)	−0.107(0.014)	−0.111(0.014)
$\frac{\partial \ln Q^w}{\partial \ln Y}$	α_2	1.154(0.117)	0.733(0.040)	0.756(0.048)
<i>Non-OPEC supply</i>				
$\frac{\partial \ln Q^{no}}{\partial \ln P}$	β_1	0.322(0.034)	0.242(0.021)	0.225(0.019)
$\frac{\partial \ln Q^{no}}{\partial \ln W^{no}}$	β_2	−0.758(0.372)	−0.302(0.180)	−0.218(0.180)
<i>OPEC supply</i>				
$\frac{\partial \ln MC^c}{\partial \ln Q^o}$	π_1^d	1.545(0.904)	−0.106(0.997)	−0.966(0.558)
$\frac{\partial \ln MC^c}{\partial \ln W^o}$	π_2^d	1.516(0.247)	1.625(0.159)	1.788(0.188)
λ		0.655(0.035)	0.354(0.047)	0.381(0.049)

Notes: We use quarterly data for the period 1986:Q1–2016:Q4. In OPEC core, the dominant firm consists of Kuwait, Saudi Arabia, UAE and Qatar. Other countries that are OPEC members are assumed to be price takers. Cost of production of the new fringe is a weighted average of cost of production of non-OPEC members and cost of production of the original OPEC members, with weights equal to production of non-OPEC countries and production of non-core OPEC countries relative to total fringe production. Column 2 uses three lags in the dominant firm model, and column 3 uses eight lags in the dominant firm model. The heteroskedasticity and autocorrelation consistent (HAC) standard errors are shown in parenthesis.

whereas the income elasticity is as low as 0.32 (0.73 for the period 1986–2016). In contrast, for the subperiod, 2001–2016, the demand elasticities, as well as the non-OPEC supply elasticities, are rather similar to the ones for the whole period (1986–2016). Finally, when using the global consumer price of oil products as the explanatory variable in the demand function, demand and non-OPEC supply elasticities do not change much (in absolute terms).

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 estimated 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. Non-OPEC countries act as a competitive fringe, whereas OPEC is envisioned to be a dominant firm, setting its price as a markup over marginal cost. 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 supply elasticities allow us to measure the degree of OPEC's market power. We find evidence that OPEC exerted substantial market power between 1986 and 2016, the period analyzed in this paper. Then, using the same data, but 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, significant demand and supply elasticities are not obtained. 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

¹⁵ As can be seen from Table 7, the results of our benchmark have a slightly better fit than the case referred to as OPEC core. This is, in particular, the case for the marginal cost of OPEC with respect to quantity, thereby, justifying our choice of benchmark. In addition, we are not aware of parameter estimates for OPEC core; it seems reasonable to pick a benchmark that can be compared with other papers.

¹⁶ More detailed results can be obtained from the authors upon request.

three decades. However, 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 lagged OPEC capacity. For the dominant firm model, we find that the estimated elasticity of marginal cost of OPEC with respect to lagged OPEC capacity is significant. Therefore, a dynamic approach to understand the role of capacity 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, Lin, 2010, Pindyck, 1978; and Jovanovic, 2013) have had limited success, which 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). An alternative strategy to incorporate resource depletion would be to add dynamics to demand—because of financial or inventory speculation¹⁷—or dynamics to supply—because of a game between OPEC and non-OPEC where producers (also) choose investment in extraction capacity. This would add persistency and volatility to prices, thereby, providing a foundation for the model to account for the big swings in prices after 2000.¹⁸ Note, however, that a game between OPEC and non-OPEC may require detailed data on costs of production for each OPEC country; we have no access to such data.

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Appendix A. Estimation methods

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

$$\mathbf{g}(\theta^c) = \begin{bmatrix} Z_t (\ln Q_t^w - \mathbf{X}^{w'} \boldsymbol{\alpha}) \\ Z_t (\ln Q_t^{no} - \mathbf{X}^{no'} \boldsymbol{\beta}) \\ Z_t (\ln Q_t^o - \mathbf{X}_c^{o'} \boldsymbol{\pi}^c) \end{bmatrix},$$

where \mathbf{X}^w , \mathbf{X}^{no} and \mathbf{X}_c^o are vectors of the right-hand side variables in Eqs. (10), (11) and (12), respectively. When estimating this system of

three equations, we use the three-stage least-squares (3SLS) method. The parameter estimates $\hat{\theta}^c$ are obtained by solving

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

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, the system general method of moments (GMM) estimation is equivalent to 3SLS estimation.¹⁹

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

$$\mathbf{g}(\theta^d) = \begin{bmatrix} Z_t (\ln Q_t^w - \mathbf{X}^{w'} \boldsymbol{\alpha}) \\ Z_t (\ln Q_t^{no} - \mathbf{X}^{no'} \boldsymbol{\beta}) \\ Z_t (\ln P_t - \ln m(\alpha_1, \beta_1, s_t^o) - \mathbf{X}_d^{o'} \boldsymbol{\pi}^d) \end{bmatrix},$$

where \mathbf{X}_d^o is the vector of the right-hand side variables in Eq. (13) except the markup.²⁰ The weighting matrix is evaluated at $(Z'Z)^{-1}$.²¹

Appendix B. Construction of confidence intervals

We compute confidence intervals by 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 values $[\ln \widehat{Q}_t^w, \ln \widehat{Q}_t^{no}, \ln \widehat{P}_t]$ plus a resampled residual $u_j^* = [u_{ij}^{w*}, u_{ij}^{no*}, u_{ij}^{o*}]$. For the j th repetition, we use the empirical distribution of the predicted errors (Fox, 2008; MacKinnon et al., 2009):

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

(* 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 of

¹⁹ We have

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

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

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

²⁰ Although both the markup and the marginal cost of OPEC are functions of OPEC supply, this should not cause a multicollinearity problem because, by using a moment condition-based method to estimate the model (GMM), we handle the endogeneity of OPEC supply adequately.

²¹ The variance of this estimator is given by

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

where $\widehat{G} = \frac{\partial \mathbf{g}(\widehat{\theta}^d)}{\partial \theta^d}$ and $\widehat{S} = \frac{1}{N} \sum Z_t \widehat{u}_t \widehat{u}_t' Z_t'$.

¹⁷ Kilian and Murphy (2014) develop a structural model for the global crude oil market and estimate demand elasticities when changes in oil inventory are taken into account. Their results suggest that the 2003–2008 oil price surge was not due to speculative trading.

¹⁸ Another potential source of volatility are OPEC announcements about, for example, changes in production. For studies on how OPEC announcements may have impact on oil prices, see, for example, Lin and Tamvakis (2010), Schmidbauer and Rösch (2012) and Loutia et al. (2016).

the errors. As discussed by MacKinnon et al. (2009), in bootstrap hypothesis testing the data should be resampled under the null hypothesis.

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

Appendix C. Formal test of OPEC market power

Consider two competing hypotheses. Let $H_d : E[g(\theta^d)] = 0$ be the null hypothesis under the dominant firm model. Similarly, let $H_c : E[g(\theta^c)] = 0$ be the hypothesis under the competitive model. Smith (1992) proposes the following Cox-type statistical test to discriminate H_d against H_c . The Cox-type statistic $b_T(H_d|H_c)$ is computed as

$$b_T(H_d|H_c) = \hat{g}_T' \hat{\Sigma}_c^{-1} \hat{A}_T T^{\frac{1}{2}} \hat{h}_T \quad (16)$$

where $\hat{A}_T = T^{-1} Z' Z \hat{\Sigma}_d^{-1}$, with moment conditions $\hat{g}_T = T^{-1} Z' \hat{u}^c$ and $\hat{h}_T = T^{-1} Z' \hat{u}^d$, and variances $\hat{\Sigma}_d$ and $\hat{\Sigma}_c$.²² T denotes the number of observations.

Smith (1992) shows that under H_c the test statistic follows a normal distribution with zero mean and variance ω_d^2 given by

$$\omega_d^2 = \text{plim}[\hat{g}_T]' \hat{\Sigma}_c^{-1} A_d M_D A_d' \hat{\Sigma}_c^{-1} \text{plim}[\hat{g}_T], \quad (17)$$

where $M_D = I - H(H' \hat{\Sigma}_d^{-1} H)^{-1} H' \hat{\Sigma}_d^{-1}$, $H = E\left[\frac{\partial h_T}{\partial \theta^d}\right]$ and $A_d = I$. This result allows us to test whether there is evidence that our dominant firm model (under H_d) can be rejected against the alternative competitive model (H_c).

Using the estimates from Section 4.1.1 (see Table 1), we compute the Cox-type statistic under the hypothesis H_d using Eq. (16). We obtain a value for the statistic of -0.69 . We then compute the standard error using Eq. (17); we find $\omega_d/\sqrt{T} = 0.62$. Under normality the 95% confidence interval under the hypothesis H_d is $[-1.90, 0.52]$. The mean 0 is included in the 95% interval under the hypothesis H_d . Thus, we find that there is no evidence to reject H_d (the dominant firm model) against H_c (the competitive model).

We also test if there is sufficient evidence to reject the competitive model in favor of the dominant firm model.²³ We reverse the hypotheses and let H_c be the null hypothesis under the competitive model and H_d the alternative hypothesis under the dominant firm model. We compute the Cox-type statistic for H_c (under the competitive model) against H_d (under the dominant firm model). The value obtained for the Cox statistic is 16,214 and its standard error is 151.65. The 95% confidence interval under the null hypothesis of the competitive model is $[15,917, 16,511]$, which is far above the mean 0. Thus, we can strongly reject the null hypothesis of the competitive model H_c against the dominant firm model H_d .

References

Alhajji, A.F., Huettner, D., 2000. OPEC and world crude oil markets from 1973 to 1994: cartel, oligopoly, or competitive? *Energy J.* 21, 31.
Alkhathlan, K., Gately, D., Javid, M., 2014. Analysis of Saudi Arabia's behavior within OPEC and the world oil market. *Energy Policy* 64, 209–225.

Almoguera, P.A., Douglas, C.C., Herrera, A.M., 2011. Testing for the cartel in OPEC: noncooperative collusion or just noncooperative? *Oxf. Rev. Econ. Policy* 27 (1), 144–168.
Boug, P., Cappelen, Å., Swensen, A.R., 2016. Modelling OPEC Behavior. Theory and Evidence. Discussion Papers 843. Statistics Norway.
Brémond, V., Hache, E., Mignon, V., 2012. Does OPEC still exist as a cartel?. An empirical investigation. *Energy Econ.* 34, 125–131.
Bresnahan, T.F., 1982. The oligopoly solution concept is identified. *Econ. Lett.* 10, 87–92.
Bresnahan, T.F., 1989. Empirical Studies of Industries with Market Power. *Handbook of Industrial Organization* 2, Ch. 17.
Brook, A.M., Price, R., Sutherland, D., Westerlund, N., André, C., 2004. Oil Price Developments: Drivers, Economic Consequences and Policy Responses. OECD Economics Department Working Papers No. 412.
Cairns, R.D., Callucura, E., 2012. OPEC: Market failure or power failure? *Energy Policy* 50, 570–580.
Colgan, J.D., 2014. The emperor has no clothes: the limits of OPEC in global oil market. *Int. Organ.* 68, 599–632.
Cooper, J.C.B., 2003. Price elasticity of demand for crude oil: estimates for 23 countries. *OPEC Rev.* 27 (1), 1–8.
Dahl, C., 1993. A survey of oil demand elasticities for developing countries. *OPEC Rev.* 17 (Winter), 399–419.
Dahl, C., Yücel, M., 1991. Testing alternative hypotheses of oil producer behavior. *Energy J.* 12 (4), 117–137.
Dees, S., Karadeloglou, P., Kaufmann, R.K., Sanchez, M., 2007. Modelling the world oil market: assessment of a quarterly econometric model. *Energy Policy* 35, 179–191.
Eckbo, P., 1976. *The Future of World Oil*. Ballinger, Cambridge (Mass).
EIA, 2010. Oil and Gas Lease Equipment and Operating Costs 1994 through 2009. U.S. Energy Information Administration. from https://www.eia.gov/pub/oil_gas/natural_gas/data_publications/cost_indices_equipment_production/current/coststudy.html.
EIA, 2017. Monthly Energy Review, U.S. Energy Information Administration. <http://www.eia.gov/totalenergy/data/monthly/>.
Fagan, G., Henry, J., Mestre, R., 2001. An Area-Wide Model (AWM) for the Euro Area. European Central Bank Working Paper No. 42.
Fattouh, B., Mahadeva, L., 2013. OPEC: what difference has it made? *Ann. Rev. Resour. Econ.* 5, 427–443.
Federal Reserve Bank of St. Louis, 2017. Spot Oil Price: West Texas Intermediate, FRED Economic Data. from <http://research.stlouisfed.org/fred2/series/OILPRICE>.
Fox, J., 2008. *Applied Regression Analysis and Generalized Linear Models*. Sage.
Gately, D., Huntington, H.G., 2002. The asymmetric effects of changes in price and income on energy and oil demand. *Energy J.* 23 (1), 9–55.
Global Financial Data <https://www.globalfinancialdata.com/About/about.html>.
Graham, D.J., Glaister, S., 2004. Road traffic demand elasticity estimates: a review. *Transp. Rev.* 24 (3), 261–274.
Griffin, J.M., 1985. OPEC behavior: a test of alternative hypothesis. *Am. Econ. Rev.* 75 (5), 954–962.
Griffin, J.M., Schulman, C.T., 2005. Price Asymmetry: A Proxy for Energy Saving Technical Change? Bush School Working Paper No. 405.
Gulen, S.G., 1996. Is OPEC a cartel? Evidence from cointegration and causality tests. *Energy J.* 17 (2), 43–57.
Hamilton, J.D., 2009. Understanding crude oil prices. *Energy J.* 30 (2), 179–206.
Hansen, P.V., Lindholt, L., 2008. The market power of OPEC 1973–2001. *Appl. Econ.* 40, 2939–2959.
Hassler, J., Krusell, P., Olovsson, C., 2012. Energy-Saving Technical Change. NBER Working Paper No. 18456.
Hnyilicza, E., Pindyck, R.S., 1976. Pricing policies for a two-part exhaustible resource cartel: the case of OPEC. *Eur. Econ. Rev.* 8 (2), 136–154.
Hotelling, H., 1931. The economics of exhaustible resources. *J. Polit. Econ.* 39 (2), 137–175.
Huppmann, D., Holz, F., 2012. Crude oil market power – a shift in recent years? *Energy J.* 33 (4), 1–22.
IEA Energy Balances of non-OECD countries, OECD, Paris.
IEA Energy Prices and Taxes, OECD, Paris.
IEA Oil Market Report, <https://www.iea.org/oilmarketreport/omrpublic/>.
IHS CERA, 2000. Upstream Costs – Why the Gap Will Widen. Cambridge Energy Research Associates, Cambridge, MA.
Jones, C.T., 1990. OPEC behaviour under falling prices: implications for cartel stability. *Energy J.* 11 (3), 117–129.
Jovanovic, B., 2013. Bubbles in prices of exhaustible resources. *Int. Econ. Rev.* 54 (1), 1–34.
Kaufmann, R.K., 2004. Does OPEC matter? An econometric analysis of oil price. *Energy J.* 25 (4), 67–90.
Kaufmann, R.K., 2005. Oil and the American Way of Life: Don't Ask, Don't Tell. http://vmsstreamer1.fnal.gov/VMS_Site_03/Lectures/Colloquium/050601Kaufmann/.
Kaufmann, R.K., Bradford, A., Belanger, L.H., McLaughlin, J.P., Miki, Y., 2008. Determinants of OPEC production: implications for OPEC behavior. *Energy Econ.* 30, 333–351.
Kilian, L., 2009. Not all oil price shocks are alike: disentangling demand and supply shocks in the crude oil market. *American economic review. Am. Econ. Assoc.* 99 (3), 1053–1069.
Kilian, L., Murphy, D.P., 2014. The role of inventories and speculative trading in the global market for crude oil. *J. Appl. Econ.* 29 (3), 454–478.
Kiswani, K.M., 2016. Does OPEC act as a cartel? Empirical investigation of coordination behavior. *Energy Policy* 97, 171–180.

²² Recall that the variances are $\hat{\Sigma}_c = \text{var}(T^{-\frac{1}{2}} Z' u^c)$ and $\hat{\Sigma}_d = \text{var}(T^{-\frac{1}{2}} Z' u^d)$.

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- Krichene, N., 2002. World crude oil and natural gas: a demand and supply model. *Energy Econ.* 24, 557–576.
- Krichene, N., 2006. World Crude Oil Market: Monetary Policy and the Recent Oil Shock. IMF Working Paper No. 62.
- Lin, C.-Y.C., 2010. An Empirical Dynamic Model of OPEC and Non-OPEC. Working paper, University of California at Davis.
- Lin, C.Y.C., 2011. Estimating supply and demand in the world oil market. *J. Energy Dev.* 34 (1/2), 1–32.
- Lin, S.X., Tamvakis, M., 2010. OPEC announcements and their effects on crude oil prices. *Energy Policy* 38, 1010–1016.
- Loutia, A., Mellios, C., Andriosopoulos, K., 2016. Do OPEC announcements influence oil prices? *Energy Policy* 90, 262–272.
- Mabro, R., 1998. OPEC behaviour 1960–1998: a review of the literature. *J. Energy Lit.* IV.1, 3–27.
- MacKinnon, J.G., 2009. Bootstrap hypothesis testing. In: Belsley, D.A., Kontoghiorghes, E.J. (Eds.), *Handbook of Computational Econometrics*. John Wiley & Sons Ltd., Chichester, UK. <https://doi.org/10.1002/9780470748916.ch6>.
- Okullo, S.J., Reynès, F., 2016. Imperfect cartelization in OPEC. *Energy Econ.* 60, 333–344.
- OPEC, 2017. Brief History. Organization of the Petroleum Exporting Countries. from http://www.opec.org/opec_web/en/about_us/24.htm.
- Pindyck, R.S., 1978. Gains to producers from the cartelization of exhaustible resources. *Rev. Econ. Stat.* 60 (2), 238–251.
- Schmidbauer, H., Rösch, A., 2012. OPEC news announcements: effects on oil price expectation and volatility. *Energy Econ.* 34, 1656–1663.
- Smith, J.L., 2005. Inscrutable OPEC? Behavioral Tests of the Cartel Hypothesis. *Energy J.* 26 (1), 51–82.
- Smith, J.L., 2009. World oil: market or mayhem? *J. Econ. Perspect.* 23 (3), 145–164.
- Smith, R., 1992. Non-nested tests for competing models estimated by generalized method of moments. *Econometrica* 60 (4), 973–980.
- Spilimbergo, A., 2001. Testing the hypothesis of collusive behavior among OPEC members. *Energy Econ.* 23, 339–353.
- Stock, J.H., Watson, M.W., 1993. A simple estimator of cointegrating vectors in higher order integrated systems. *Econometrica* 61, 783–820.
- Suslow, V.Y., 1986. Estimating monopoly behavior with competitive recycling: an application to Alcoa. *RAND J. Econ.* 17 (3), 389–403.
- U.S. Bureau of Labor Statistics, 2017a. Consumer Price Index: All Urban Consumers – (CPI-U) US City Average (All Items). from <http://www.bls.gov/cpi/>.
- U.S. Bureau of Labor Statistics, 2017b. Bureau of Labor Statistics. Oil and Gas Field Machinery and Equipment Mfg, Producer Price Index Industry Data. from <http://data.bls.gov/cgi-bin/surveymost?pc>.