Global Oil Markets Revisited – Cartel or Stackelberg Market?

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Abstract

This paper investigates the existence of market power and the sequentiality of games in the crude oil market. In particular, we examine whether Saudi Arabia acts as a Stackelberg leader or in a simultaneous-move framework, under a number of market power scenarios ranging from perfect competition to cartel. We develop a numerical simulation model that is formulated as a complementarity problem, allowing for the possibility of strategic interaction between the players. In contrast to other partial equilibrium models of natural resource markets, the model proposed in this paper explicitly takes into account the influence of price pools such as Brent and WTI where arbitrageurs exploit price differentials that are not justified by transport costs. Our results indicate that all suppliers exert market power while Saudi Arabia acts as Stackelberg leader. More specifically, we find that OPEC members do not act cooperatively, i.e. they do not maximise joint profits. Rather, they exhibit strategic non-cooperative behaviour, rejecting the notion that OPEC is a cartel.

Keywords: crude oil, market structure, cartel, simulation model, price indices

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1 Introduction

The question whether the Organisation of Petroleum Exporting Countries (OPEC) forms a cartel and exerts market power has frequently been asked in economic literature since the first oil crisis in 1973. Attempts to explain the market structure range from cartel to a perfectly competitive market. OPEC is frequently cited as the standard example for a cartel and a number of possible ways of its functioning have been proposed to describe its behaviour, as summarised by Dahl (2004). Clearly, the importance of OPEC on the global crude oil market and, moreover, of Saudi dominance within the group cannot be ignored. Therefore, the sequence of the suppliers' decisions – and potential leadership in decision marking – should be considered when investigating the market structure of the crude oil market.

Despite of (or rather due to) the extensive research on the matter, the conclusions on the market structure are ambiguous at best, contradictory at worst. Lin (2009), for instance, uses a Hotelling model to test the hypothesis of collusion. While she finds that OPEC behaved like a monopolist in the first decades of its existence, the market would have been competitive over the last twenty years. Böckem (2004) applies New Empirical Industrial Organization theory and concludes that OPEC behaves as a price-leader while all other suppliers are price-takers. Yet another approach was brought forward by Alhajji and Huettner (2000a), arguing that OPEC is neither a cartel nor competitive but rather something "in between": the organization consists of several rather diverse members that pursue different strategies. They argue that OPEC did have success in recent years in raising prices above competitive levels, but they attribute it to other economic and technical factors (e.g., available production capacities in the OPEC countries) than a functioning cartel structure.

A different line of research focuses on the behaviour of individual OPEC members. Dibooglu and AlGudhea (2007) look at the pattern of cheating in the cartel structure, i.e. the over-production of the OPEC quota by individual members. They find that small infringements of the quota are usually tolerated, but large incidences of cheating trigger Saudi Arabia to respond with a tit-for-that strategy. Hartley and Medlock (2008) focus on the distinction between National Oil Companies (NOC) and International Oil Companies (IOC). Political interference in government-owned entities may lead to a bias towards short-term revenue maximization to please political constituencies. Alhajji and Huettner (2000b) investigate the target revenue approach: observing that small oil-producing countries might only be able to reasonably reinvest a certain amount of profits within their domestic economy, these countries might aim at generating a certain level of income rather than maximizing profits. Using an econometric test, they find that OPEC, as a whole, is indeed not acting as a profit maximiser.

A third focus in oil market research is on prices. Wirl (2008) examines possible explanations for the high oil prices in 2007. He concludes that political reasons for the price spike can be rejected; instead, a demand shock can explain the price jump. Bentzen (2007) focuses on the question whether the crude oil market is regionalised or not. He identifies a bi-directional causality in oil price movements between the WTI (West Texas Intermediate, USA) and Brent (Northwestern Europe) indices on the one hand and the OPEC price basket and the Dubai index on the other. He therefore concludes that the global market is integrated.

The model presented in this paper combines three aspects: market power of OPEC suppliers, the sequentiality of decisions, and the influence of liquid spot markets and price indices in an integrated market. Al-Qahtani et al. (2008), in another recent simulation model, consider the crude oil market only from the profit-maximizing point of view of Saudi Arabia; strategic decisions of other players are not included. Their results indicate that Saudi Aramco could increase profits by reducing production by approximately 4 %. Our Nash-Cournot model, in contrast, allows for strategic behaviour by other OPEC members and non-OPEC players, and we compare simultaneous-move and two-stage games. Our results lead to the conclusion that OPEC does not form a cartel, but that the market is not perfectly competitive either. The crude oil market can rather be described as a Nash-Cournot market, in which Saudi Arabia acts as Stackelberg leader; all OPEC members exert market power and maximise profits independently, while other producers act as a competitive fringe.

In section 2, we present the model. To take account of liquid spot markets and arbitrageurs, the price in each consumption node must equal the price in the nearest spot market plus transport costs. In section 3, we present a numerical application comparing several market power theories in both a simultaneous move and sequential game structure. Section 4 concludes.

2 The Model

Nash-Cournot partial equilibrium models have recently been used to investigate global energy resource markets, such as the natural gas market (e.g., Boots et al., 2004; Holz et al., 2008; and Egging et al., 2008) and the steam coal market (Haftendorn and Holz, 2008). These models are formulated as mixed complementarity problems (MCP). In these models, price discrimination between import markets can occur if suppliers exert market power, since arbitrageurs are usually not considered. This might be appropriate for resources where no liquid spot market exists (yet) and where trade is often carried out through long-term contracts. However, price discrimination is implausible in a highly integrated and liquid market such as the crude oil market.

Analyzing regional pool electricity markets, Hobbs (2001) has proposed a Nash-Cournot model where the price is determined in a pool hub and the final demand price in each node equals the pool price plus transport costs. Therefore, price discrimination between demand nodes cannot occur. In our model, we combine these two approaches, namely modelling the global market and explicitly barring price discrimination.

Assuming arbitrageurs with competitive (price-taking) behaviour, Metzler et al. (2003) show that the following market setups yield identical results:

- The arbitrageurs solve a profit maximization problem parallel to the suppliers,
- The suppliers are Stackelberg leaders and anticipate the actions by the arbitrageurs that are followers,
- A pool Cournot market of suppliers.

Consequently, we do not need to introduce a distinct profit maximization problem for the arbitrageur, but can include the arbitrageur's problem directly in the optimization program of the Cournot trading entities and in the inverse demand function. In particular, we require the final demand price to equal the pool hub price plus transport costs.

In contrast to Hobbs (2001), we introduce more than one pool because there are several important spot markets in the global oil market. A simplification necessary for the tractability of the program is the assumption that final demand at node n can only buy from and sell to one specific pool i, namely the one with the lowest transport costs to the node. The parameter $\vartheta_{n,i}$ of node n equals 1 for this pool and 0 otherwise.

2.1 The supplier

Oil companies extract crude oil and sell it downstream, usually to refineries. We separate these two activities in a production entity P and a trading entity T. The production entity at node n carries out the production of crude oil (denoted by $Prod^{P}{}_{n}$). The trading entity then arranges the transportation and sales of crude oil to the downstream market. The split-up of the two activities allows modelling either a market where each player optimises independently, or joint profit maximization by an OPEC cartel by introducing a single cartel trader that buys the total OPEC production and sells it downstream.

The production entity

The production entity *P* of the supplier operates at node *n* and can sell to its trading entity *T* for an intra-company price of $\varphi^{T}{}_{t,n}$ equal to marginal cost. It aims at maximizing its profit, given its production cost function $Cost^{P}{}_{n}(\cdot)$ at node *n* that is of the same type as used by Aune et al. (2001) for fossil fuel supply costs. The production entity is subject to a production capacity constraint. Since we only investigate one period, we do not consider a reserves constraint. $\alpha^{Prod}{}_{n}$ is the dual variable of the capacity constraint $\left(\overline{Cap_n^P}\right)$ which can be interpreted as the shadow price of capacity. The full optimization problem of the production entity is:

$$\begin{aligned} &\max_{\text{Prod}_n^P} \quad \text{Prod}_n^P \cdot \phi_{t,n}^T - Cost_n^P\left(\text{Prod}_n^P\right) \\ &\text{s.t.} \quad \text{Prod}_n^P \le \overline{Cap}_n^P, \quad \left(\alpha_n^{\text{Prod}}\right) \end{aligned} \qquad (1)$$

The trading arm

The trading arm forms the link between the oil well and consumers. It receives the crude oil from its respective production entity, transports it either by pipeline ($Flow^{T}$) or ship ($Ship^{T}$) to a consumption node and sells it to final demand *R* ($Sales^{T\rightarrow R}$). The trading arm aims at maximizing its profits in the downstream market. The model allows for imperfect competition à la Cournot. If the trader is a Cournot player, he knows the inverse demand function $\Pi^{R}{}_{n}(\cdot)$ at node *n*; he can therefore exert market power to influence the market price by deliberately withholding supplies. In our model formulation, we include a parameter δ^{T} to be multiplied with the price mark-up of a strategic players. Hence, a value of $\delta^{T} = 1$ makes the trader a Cournot player, while a value of 0 means that he is acting competitively. Under the assumption of no-price-discrimination, the market-clearing price at node n must equal the pool equilibrium price plus transport costs, namely $\pi^{Pool}_i + TC_{i\to n}$ for the respective pool i.

$$\max_{\substack{Sales^{T\to R}_{t,n},\\ Flow^{T}_{t,n,m}, Ship^{T}_{t,n,k}}} \sum_{n\in N} \left[\begin{array}{l} Sales^{T\to R}_{t,n} \cdot \left[\delta^{T}_{t,n} \cdot \Pi^{R}_{n}(\cdot) + \left(1-\delta^{T}_{t,n}\right) \cdot \sum_{i} \vartheta_{n,i} \cdot \left(\pi^{Pool}_{i} + TC_{i\to n} \right) \right] \\ - \sum_{m\in A(n)} Flow^{T}_{t,n\to m} \cdot TC^{Pipe}_{n\to m} - \sum_{k\in Pt} Ship^{T}_{t,n\to k} \cdot TC^{Ship}_{n\to k} - \mathrm{Prod}^{P}_{n} \cdot \phi^{T}_{t,n} \end{array} \right]$$

$$\begin{aligned} s.t.\quad & Sales^{T\to R}_{t,n} - \mathrm{Prod}^{P}_{n} + \sum_{m\in A(n)} Flow^{T}_{t,n\to m} + \sum_{k\in Sea} Ship^{T}_{n\to k} \\ & - \sum_{n\in A(l)} Flow^{T}_{l\to n} - \sum_{h\in Pt} Ship^{T}_{h\to n} = 0, \quad \left(\phi^{T}_{t,n}\right) \quad \forall t \end{aligned} \tag{2}$$

Here, *A(n)* specifies all countries which can be reached from country n by pipeline, while *Pt* is the set of all ports. The linear transport costs $TC^{Pipe}_{n\to m}$ and $TC^{Ship}_{n\to k}$ are distance-based and accounted for at the exporting node and borne by the supplier.

2.2 The arbitrageur

There exist several pools $i \in I$ where arbitrageurs are located. They exploit price differentials between consumption nodes in excess of transport costs by selling and buying between nodes.[1] The arbitrageur is a non-strategic, price-taking player and its decisions (on pool price, arbitrage quantity) and constraints can be directly included in the trading entities' and final demand's equations. Trading entities sell to final demand directly, so the crude oil is not necessarily directed via the pool node; only the amounts bought or sold by the arbitrageur $Arbit^{Pool}_{i,n}$ pass

[1] Since all arbitrageurs are identical at the pool node from which they operate, we assume that there is one arbitrageur per pool node.

through the pool.[2] However, as the arbitrage quantities are the marginal quantities sold on the market, they are price-setting.

The arbitrageur can be neither a net producer nor a net consumer; the sum of its purchases must equal its sales. This condition is included in the trading entities' optimization problem.

$$\sum_{n \in N} Arbit_{i,n}^{Pool} = 0, \quad \left(\beta_i^{Pool}\right) \quad \forall i \in I \tag{3}$$

2.3 Final demand for crude oil

The suppliers sell the crude oil downstream in the oil sector value chain, usually to refineries (R). Since we are aiming at modelling the international crude oil trade and analyzing the market power of crude oil suppliers, we do not include the market for oil products. Demand for crude oil in country n is modelled via a linear inverse demand function of the type $DemInt - DemSlp \cdot q$. The demand function parameters are derived from a reference data point (quantity, price) and an assumption on the value of the price elasticity. Using the standard definition of the price elasticity $\varepsilon = \frac{y - y^{ref}}{p - p^{ref}} \cdot \frac{p}{y}$, we have $DemInt = p^{ref} - b \cdot y^{ref}$ and $DemSlp = \frac{p^{ref}}{y^{ref}} \cdot \frac{1}{\varepsilon}$. We require the final demand price to equal the pool hub price (from the closest pool) plus transport costs to the final demand node, i.e., $\sum_{i \in I} \vartheta_{n,i} \cdot \left(\pi_i^{Pool} + TC_{i \to n}\right)$. The market clearing condition is:

[2] Note that this value can be positive or negative depending on whether the Arbitrageur is a net buyer or net seller at that node.

$$DemInt_n^R - DemSlp_n^R \cdot \left[\sum_{t \in T} Sales_{t,n}^{T \to R} + \sum_{i \in I} \vartheta_{n,i} \cdot Arbit_{i,n}^{Pool} \right] - \sum_{i \in I} \vartheta_{n,i} \cdot \left(\pi_i^{Pool} + TC_{i \to n} \right) = 0, \qquad (4)$$

$$\left(\beta_n^{\text{Price}} \right) \quad \forall n \in N$$

The price of crude oil in the pool π^{Pool} is determined as the dual to the constraint $\sum_n \beta_{\text{n}}^{\text{Price}} = 0$.

In the appendix we provide the complete mathematical formulation of the complementarity model consisting of the Karush-Kuhn-Tucker conditions of the optimization problems and the equilibrium conditions. For a comparison of the pool market model to the setup with price discrimination used in modelling natural gas and coal markets, see Huppmann and Holz (2009).

Simultaneous move vs. sequential games

The model described thus far is a standard simultaneous move (i.e. static) game; all suppliers decide in parallel about their own optimal strategy, given the optimal strategies of all other players. This results in a standard Nash equilibrium, formulated as a MCP. However, the game changes if one of the players is in a position to act first, anticipating the reaction of the other agents to its own decision. Computationally, this dynamic game is a Mathematical Problem under Equilibrium Constraints (MPEC). The supplier in question – the Stackelberg leader – maximises its profits under the constraint of an equilibrium in the second stage of the game, which is identical to the one-level (Cournot) game described above.

The numerical simulation model is formulated in the General Algebraic Modeling System (GAMS) language. The PATH solver (Ferris and Munson, 2000) is used to solve the MCP model, while the NLPEC solver is used for the MPEC model.

3 A Numerical Application

We use the model proposed above to simulate the global crude oil market under a number of market structure and market power scenarios, and compare model results to observed quantities and prices in the real world. The data set comprises more than 85% of global crude oil production and consumption, including all OPEC and OECD members and other countries with considerable production or consumption. A list of countries is given in Table 1. The pool nodes used in the pool model are USA (WTI), UK (Brent) and United Arab Emirates (Dubai/OPEC basket).

Region	Countries					
America	Brazil	P & C	Canada	P & C	Ecuador	P
	Mexico	P & C	USA	P & C	Venezuela	P
Asia Pacific	Australia	C	China	P & C	India	C
	Indonesia	P & C	Japan	C	Korea	C
	New Zealand	C	Taiwan	C		
Africa	Algeria	P	Angola	P	Libya	P
	Nigeria	P				
Middle East	Iran	P & C	Iraq	P	Kuwait	P
	Qatar	P	Saudi Arabia	P & C	United Arab Emirates	P
Europe	Austria	C	Belgium	C	Czech Republic	C
	Denmark	C	Finland	C	France	C
	Germany	C	Greece	C	Hungary	C
	Ireland	C	Italy	C	The Netherlands	C
	Norway	P & C	Slovakia	C	Turkey	C
	United Kingdom	P & C				
Former SU	Kazakhstan	P	Russia	P & C		

Note: *P* Producer
C Consumer

Table 1: Countries included in the model data set

We use 2006 as the base year.[3] Consumption and production quantities and reference prices are collected from IEA (2008) and BP (2008); wherever available, we have opted for quantities excluding natural gas liquids (NGL). An overview of demand elasticity estimates is given in

[3] Indonesia is included as an OPEC member country, since it only withdrew from the organisation in January 2009; Ecuador was not a member at that time and is not counted as an OPEC member.

Fattouh (2007), ranging from 0.001 to −0.11 in the short run and 0.038 to −0.64 in the long run; we choose −0.10 in this paper. A sensitivity analysis with other elasticity values can be found in Appendix B. Production cost data is gathered from Aguilera et al. (2009).[4] Transport costs are distinguished between pipeline and tanker shipping cost and are derived from BGR (2003).

Lacking coherent data on maximum production capacity by country, we assume that all countries are producing at 95% of capacity in the base year reference values. While this may underestimate true potential production capacity, it allows identifying countries that could gain from raising production without distorting our results too much.[5] A case *sui generis* should be made for Saudi Arabia: it is widely accepted that the Saudi production capacity is considerably higher than actual production to deter other OPEC members from over-producing their quota. It is, however, irrelevant from the approach we pursue in this work whether production capacity is indeed a binding constraint or whether production capacity is deliberately kept idle.

Game structure and market power scenarios

In line with the existing energy market modeling literature and the theories generally brought forward to describe the crude oil market, the following market power scenarios are compared…

…in the simultaneous-move framework (MCP model):

- the market is perfectly competitive; no supplier exerts market power (*Competition*)
- all suppliers exert market power à la Cournot (*Nash-Cournot*)

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[4] The estimates provided are average total production costs; we assume that marginal production costs plus transport to the export hub are three times average production costs and use this estimate to derive a quadratic cost function.

[5] In none of our scenario results is total output higher than the reference output.

- OPEC members form an oligopoly and exert market power, but optimise independently, while other suppliers form a competitive fringe (*Oligopoly*)
- OPEC jointly maximises profits and exerts monopoly market power as a cartel while other suppliers form a competitive fringe (*Cartel*)

…in the Stackelberg leadership game (MPEC model), with Saudi Arabia acting as Stackelberg leader:[6]

- the rest of the market is perfectly competitive (*Competition SB*)[7]
- all other suppliers exert market power à la Cournot (*Nash-Cournot SB*)
- OPEC members besides Saudi-Arabia form an oligopoly and exert market power, but optimise independently, while other suppliers form a competitive fringe (*Oligopoly SB*)

Results for the final demand prices (i.e. crude oil prices at the refinery) in the USA and the UK are given in Figure 1. In a perfectly competitive market, prices would be only about half as high as actually observed in 2006, while a functioning cartel could enforce a price level three times as high. Prices observed in the real world are closest to the *Oligopoly* and the *Nash-Cournot SB* market structure.

Results for quantities produced by selected countries are depicted in Figure 2. One can distinguish four groups of suppliers: The competitive fringe (China, USA, and others) produces at full capacity whenever prices exceed marginal cost; Russia, on the other hand, takes advantage of its dominant geographic position vis-à-vis Central Europe whenever it exerts market power. Russia drastically reduces production in the *Nash-Cournot* and *Nash-Cournot SB*

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[6] There is literature suggesting that OPEC as a whole is the Stackelberg leader (e.g. Böckem, 2004); we decided against this since preliminary model results indicated that OPEC does not act as a cartel with the capability to enforce joint profit optimisation.

[7] Production quantities in *Competition* and *Competition SB* market structure are almost identical and *Competition SB* is therefore omitted in some results.

market structure, to only about 50 % of capacity. One can therefore dub it “the oligopolistic fringe”.

All OPEC members apart from Saudi Arabia produce at or close to full capacity in all scenarios apart from the cartel case. This supports the proposition that OPEC members have strong incentives to deviate from their allocated quota in the absence of effective punishment mechanisms. Only when a joint OPEC trader enforces the optimal cartel strategy (*Cartel* market structure) are higher-cost suppliers within OPEC forced to reduce their production.

Results for Saudi Arabia show a striking difference between the simultaneous-move and the Stackelberg market structure: if Saudi Arabia acts as Stackelberg leader, it produces at full capacity, thereby benefiting from a combined quantity and price effect (stemming from the withholding by the other players). Being the supplier with the lowest cost, this also holds in a perfectly competitive market (*Competition*). In simulations with market power and simultaneous decisions (*Nash-Cournot* and *Oligopoly*), however, Saudi Arabia only produces at 60 % and 40 % of capacity, respectively. This result strongly points to the conclusion that Saudi Arabia indeed is in a dominant position on the global crude oil market, akin to Stackelberg leadership.

Looking at the relative profits of Saudi Arabia and OPEC in Figure 3 confirms expected results: in the two cases where we compare one-level and two-level games, Saudi Arabia is able to increase its own profits at the expense of other suppliers if it acts as Stackelberg leader. The cartel generates the largest profits for its members[8], while OPEC’s total profits are the lowest in

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[8] In the *Cartel* market structure, the profits of the OPEC trader are shared amongst the cartel’s members according to their share of total OPEC production.

a perfectly competitive market. Because Saudi Arabia only produces at a low level in the *Oligopoly* market structure, its profits are actually higher in the perfectly competitive market.

4 Conclusions and Future Directions

This paper proposes a Nash-Cournot partial equilibrium trade model including arbitrageurs operating in spot markets; price discrimination between the import markets is thus prevented. Due to the global scope of the crude oil trade, we introduce several such spot price pools. Prices in each consumption node are required to equal the price at the nearest pool node plus transport costs in equilibrium.

Simulating the crude oil market under a number of market structure scenarios, we find that the best fit to observed prices and quantities in 2006 is obtained by the scenario in which all suppliers behave strategically while Saudi Arabia acts as a Stackelberg leader. OPEC countries exert market power vis-à-vis the downstream market, albeit not in a cooperative way; they do not jointly maximise profits as in a cartel. According to our simulation results, a cartel could enforce prices at three times the crude oil price level in 2006; in a perfectly competitive market, prices would be only about half the level observed in the real world.

There are several caveats to our approach: we simplify reality by considering crude oil as a homogenous good, neglecting quality differences of crude oil produced in different regions. Moreover, the model proposed here considers only supply and demand; we ignore speculation and the „paper oil“ market. While this is unreasonable when investigating short-term price movements, the distortions from volatile prices are less pronounced when looking at yearly averages as we do. We are aware that a Nash-Cournot model cannot adequately capture the complex collaboration mechanism within OPEC or consider questions such as cartel stability. Our results indicate that OPEC suppliers have an incentive to “over-produce” above their quota, as they produce at full capacity in almost all simulation runs. Moreover, the assumption of profit maximization based on economic fundamentals does not do justice to the complex behaviour of NOCs that have to perform more activities than only oil production and sales. An extension of our modelling approach could be to include a social welfare function to be maximised by NOCs.

Lastly, for the time being, our model covers only one period; consequently, suppliers do not consider inter-temporal optimization as proposed by Hotelling (1931). The multi-pool modelling approach can be extended to cover multiple periods, including endogenous investment in additional production capacity. The model projections regarding investment decisions could provide insights into issues such as security of supply and future price developments under different crude oil demand trajectories. This will be the subject of future research.

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Appendix A: MCP Formulation of the Model

From the optimization problems specified above we derive the following Karush-Kuhn-Tucker conditions for each agent (*P, T, R*). The arbitrageur does not explicitly solve a profit maximization problem; its constraints and equilibrium conditions are included in the other agents' problems.

- The production entity *P* of the supplier:

$$\phi_{t,n}^{T} - LC_n^P - QC_n^P \cdot \mathrm{Prod}_n^P - \alpha_n^{\mathrm{Prod}} \leq 0 \quad \perp \quad \mathrm{Prod}_n^P \geq 0 \tag{5}$$

$$\mathrm{Prod}_n^P - \overline{Cap}_n^P \leq 0 \quad \perp \quad \alpha_n^{\mathrm{Prod}} \geq 0 \tag{6}$$

- The trading arm *T* of the supplier:

$$\pi_n^R - \delta_{t,n}^T \cdot DemSlp_n^R \cdot Sales_{t,n}^{T\to R} + \beta_n^{\mathrm{Price}} \cdot DemSlp_n^R - \phi_{t,n}^T \leq 0 \quad \perp \quad Sales_{t,n}^{T\to R} \geq 0 \tag{7}$$

$$\phi_{t,n}^T - TC_{m\to n}^{Pipe} - \phi_{t,m}^T \leq 0 \quad \perp \quad Flow_{t,m\to n}^T \geq 0 \quad \forall m \in A(n) \tag{8}$$

$$\phi_{t,n}^T - TC_{k\to n}^{Ship} - \phi_{t,k}^T \leq 0 \quad \perp \quad Ship_{t,k\to n}^T \geq 0 \quad \forall k \in Pt \tag{9}$$

$$\begin{aligned} &Sales_{t,n}^{T\to R} - \mathrm{Prod}_n^P + \sum_{m\in A(n)} Flow_{t,n\to m}^T + \sum_{k\in Sea} Ship_{t,n\to k}^T \\ &- \sum_{n\in A(l)} Flow_{t,l\to n}^T + \sum_{h\in Pt} Ship_{t,h\to n}^T = 0, \quad \phi_{t,n}^T \ (\text{free}) \end{aligned} \tag{10}$$

- The following constraints of the arbitrageur are part of the trader's KKTs. This can be done because the arbitrageur behaves perfectly competitively (i.e., not strategically) and because the trader's action affects the arbitrageur's variables (cf. Hobbs, 2001, for a detailed explanation).

$$DemSlp_n^R \cdot \left[\beta_n^{\text{Price}} - \sum_{t \in T} \delta_{t,n}^T \cdot Sales_n^{T \to R} \right] - \beta_i^{Pool} = 0, \quad Arbit_{i,n}^{Pool} \left(\text{free} \right) \tag{11}$$

$$\sum_{n \in N} Arbit_{i,n}^{Pool} = 0, \quad \beta_i^{Pool} \left(\text{free} \right) \tag{12}$$

$$\sum_{n \in N} \vartheta_{n,i} \cdot \beta_n^{\text{Price}} = 0, \quad \pi_i^{Pool} \left(\text{free} \right) \tag{13}$$

- Final demand is also a constraint in the traders optimization problem, i.e., the following equation is also a KKT of the trader. Note that only the respective pool for this demand node is considered.

$$DemInt_n^R - DemSlp_n^R \cdot \left[\sum_{t \in T} Sales_{t,n}^{T \to R} + Arbit_{i,n}^{Pool} \right] - \sum_{i \in I} \vartheta_{n,i} \cdot \left(\pi_i^{Pool} - TC_{i \to n} \right) = 0, \quad \beta_n^{\text{Price}} \left(\text{free} \right) \tag{14}$$

Appendix B Sensitivity Analysis

As noted earlier, the ranges of estimated demand elasticity levels in the literature are rather wide. We therefore carry out a sensitivity analysis with respect to this parameter using values of 0.05 and 0.2 for price elasticity of demand, in addition to the value of 0.1 used in our base specification. Table 2 lists final demand prices in the UK and the USA for all market structure scenarios for all three elasticity values. If demand elasticity was indeed lower, the *Oligopoly SB* market structure could be a better description of real world observation. However, the observations regarding Saudi production levels made in Section 3 still hold, as shown in Table 3. This supports our conclusion that Saudi Arabia is a Stackelberg leader in a sequential game, with market power exerted by – at least – most suppliers, and no cartel-like collaboration mechanism within OPEC.

Demand Elasticity		0.05		0.10		0.20	
	Demand Node	UK	USA	UK	USA	UK	USA
Market Structure Scenario	Competition SB	28.45	28.69	25.76	31.06	30.81	35.86
	Competition	28.26	28.96	30.40	31.09	35.10	35.79
	Oligopoly SB	50.90	50.39	36.36	36.13	35.55	34.91
	Oligopoly	84.97	85.45	54.24	54.71	44.56	45.03
	Reference	65.00	59.15	65.00	59.15	65.00	59.15
	Nash-Cournot SB	113.16	110.08	73.62	70.67	54.43	55.67
	Nash-Cournot	143.25	136.16	88.18	84.75	61.11	59.46
	Cartel	318.31	318.78	175.29	175.76	103.96	104.43

Table 2: Sensitivity analysis for different elasticity values: Final demand (refinery) prices in US-$ / bl. in the USA and the UK

Demand Elasticity		0.05			0.10			0.20		
	Production Node	Saudi Arabia	OPEC Total	World Total	Saudi Arabia	OPEC Total	World Total	Saudi Arabia	OPEC Total	World Total
Market Structure Scenario	Competition	541.7	1816.1	3168.5	541.7	1820.2	3240.4	541.7	1820.8	3347.9
	Nash-Cournot	266.8	1546.0	2887.2	325.0	1604.2	2957.4	437.1	1716.3	3093.5
	Oligopoly	177.6	1401.1	3025.2	220.4	1494.3	3118.3	344.5	1623.7	3247.7
	Cartel	210.6	817.4	2441.4	230.8	888.6	2512.6	271.3	1029.2	2653.3
	Competition SB	541.7	1817.0	3167.9	541.7	1820.8	3245.6	541.7	1820.8	3356.0
	Nash-Cournot SB	541.7	1798.2	2957.4	541.7	1820.8	3028.2	541.7	1820.8	3137.9
	Oligopoly SB	541.7	1484.6	3108.6	541.7	1633.1	3206.8	541.7	1807.4	3342.1
	Reference	514.6	1729.8	3272.7	514.6	1729.8	3272.7	514.6	1729.8	3272.7

Table 3: Sensitivity analysis for different elasticity values: Crude oil production in million metric tons

Figures

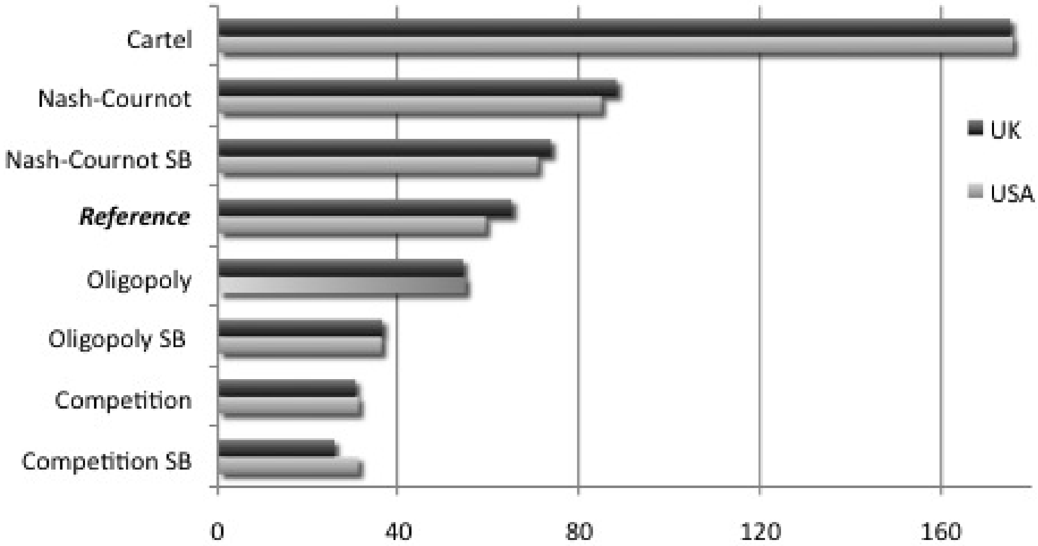

Figure 1: Final demand prices in $/barrel in the US and the UK

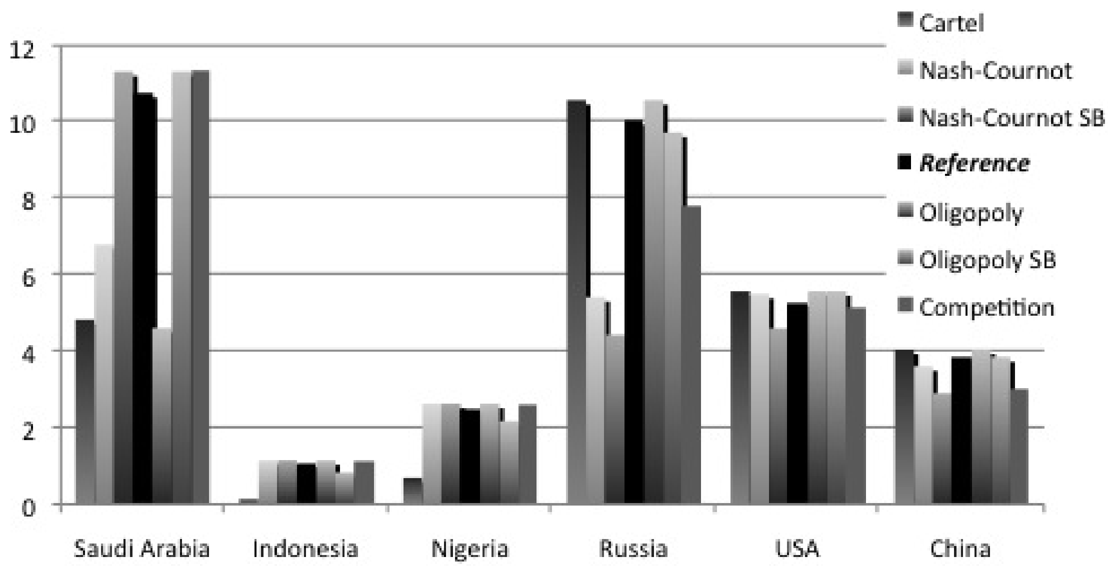

Figure 2: Production by selected countries in million barrels per day

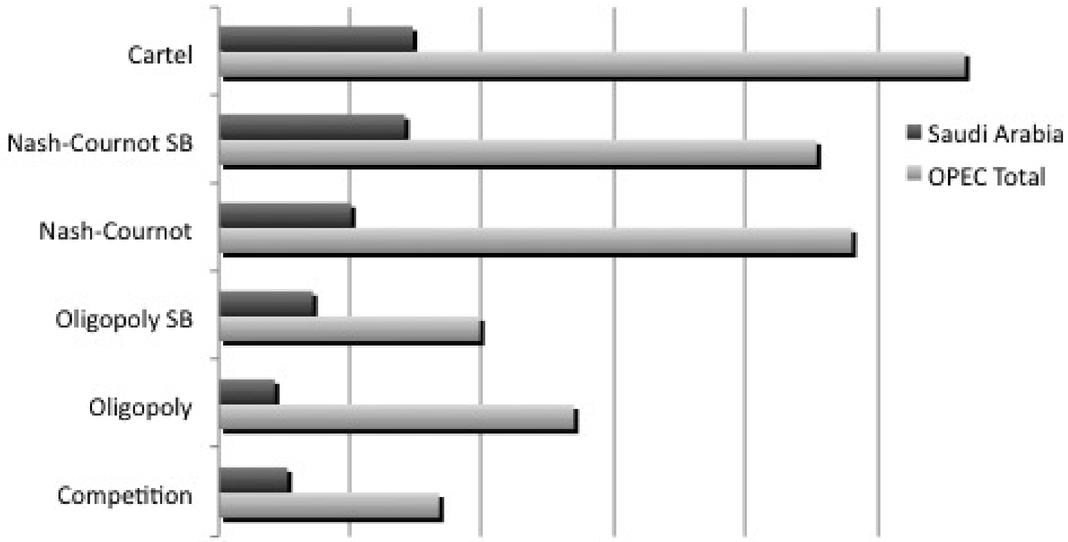

Figure 3: Relative profits of Saudi Arabia and OPEC total profits in different market structures