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OPEC, Saudi Arabia, and the Shale Revolution: Insights from Equilibrium Modelling and Oil Politics

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Abstract: Why did OPEC not cut oil production in the wake of 2014's price fall? This study aims at aiding the mostly qualitative discussion with quantitative evidence from computing quarterly partial market equilibria Q4 2011 – Q4 2015 under present short-term profit maximisation and different competition setups. Although the model performs reasonably well in explaining pre-2014 prices, all setups fail to capture low prices, which fall even beyond perfect competition outcomes. This result is robust with respect to large variations in cost parameters. Rejecting present short-term profit maximisation, as well as a qualitative discussion of Saudi Arabian politics and the shale oil revolution, lead to the conclusion that the price drop of 2014-16 was most plausibly the result of an attempt to defend market shares and to test for shale oil resilience, besides being fuelled by other factors such as rising competitiveness of alternative technologies. Although shale oil might have increased competition permanently (as supported by model results), the agreement of December 2016 should not be misunderstood as an OPEC defeat.

Keywords: Crude oil, OPEC, Shale oil, Oil price, Equilibrium modelling, Saudi Arabia, Shale revolution

JEL: Q35, Q31, O53, L71, L11, L13, C63, C61

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1. Introduction

The 2014-2016 drop in crude oil prices has been researched extensively by oil market analysts. Although results have given evidence for a variety of drivers, including decreased demand and geopolitical circumstances, the *shale oil revolution* is widely considered to be the main driver of price developments. Since 2012, crude oil production capacities in the US have nearly doubled due to the rapid growth of its shale oil industry. The term 'shale' refers (imprecisely) to conventional oil trapped in low-permeability formations and extracted by unconventional methods such as hydraulic fracking and horizontal drilling.

Why OPEC did not respond to the expanding shale production and falling prices with production cuts remains an open question. Other researchers' results in these regards fall into three main categories: (1) OPEC tried to defend its market share by flooding the market in an attempt to drive out shale producers; (2) the shale oil revolution nullified OPEC's market power, leaving its members no choice but to accept low prices; and (3) OPEC was uncertain about the potential of shale oil and needed to test its performance under low prices (Background section).

However, most discussion of OPEC's intensions are purely qualitative, with little or no quantitative evidence. This paper aims to bridge this gap with insights from computational equilibrium modelling. Specifically, I construct a model of the global crude oil market from 2011Q4 through 2015Q4 and compute market outcomes numerically under different competition setups for each quarter (Model section). The model, which is in an extension of the framework proposed by Huppmann (2013), does not aim to provide a comprehensive picture of the crude oil market, but rather an understanding of whether prices pre- and post-drop can be explained within one common framework of *business-as-usual* competition. Subsequently, I embed the results in an extended discussion about the nature of shale oil and oil politics; especially the different strategic and economic factors that might influence Saudi Arabia.

The inability of short-term profit maximisation to explain low prices (despite a reasonable model fit until late 2014) allows me to reject the claim that developments are the sole outcome of changes in market fundamentals and static competition (Results section). This is robust with respect to changes in the cost parameters, such that (a possibly not captured) increased efficiency of shale producers over time is unlikely to change this result. In the context of actual events and the deferred decision to cut production in 2016, I conclude that initial OPEC policy aimed at defending market shares against shale oil and at evaluating the elasticity of shale supply (Discussion section). The latter turned out to be more robust and resilient than expected, besides fiscal pressure from the burden of low prices on oil-dependent OPEC economies. Further developments, such as increasing pressure from climate change policies, might have strengthened incentives to flood the market, along with national politics. Saudi-Arabian-led efforts to negotiate a deal, ultimately reached in December 2016, should not (necessarily) be interpreted as the abandoning of previous strategies or as an OPEC defeat, even though the shale revolution may have permanently altered the market structure, with prices unlikely to return to pre-2014 values. This is supported by a counterfactual model setup in which

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OPEC acts as a single entity without regard to the profit distribution among its members, revealing high prices might require a coordination on high production cuts that is politically infeasible.

As mentioned, despite a large literature discussing the issue, including, for example, Baffes et al. (2015); Baumeister and Kilian (2016); Dale (2016); Fattouh et al. (2016); Khan (2017), and Aguilera and Radetzki (2015), the only study featuring a comprehensive formal discussion and a numerical calibration is Behar and Ritz (2017). However, their quantitative part is limited to predicting the strategic decision between defending market share and maximising short-term profit.

2. Background

2.1 The falling price puzzle

After the steep rise in 2008, oil prices remained on a high level until late 2014, when prices started falling. Figure 1 depicts the price trajectory from 2011 to 2015, which is the period relevant for this study. Quarterly prices fluctuate around an average of approximately 100 USD / bbl between 2011Q4 and 2014Q2. WTI Crude reached its peak quarterly in early 2012 with prices exceeding 110 USD / bbl. A quarter later it fell to 80 USD / bbl; the lowest price in that era. Henceforth, I refer to this period as the "first part" or the "high-price period" in contrast to the "second part" or "low-price period": Between 2014 Q3 and 2015 Q1, quarterly prices dropped by more than 50%. Most of this fall took place during late 2014 and ended with a quarterly average barely above 40 USD / bbl in 2015 Q1. Subsequently, oil prices recovered slightly before falling in 2015 Q3 even below.

Another development taking place concurrently is the rapid expansion of shale oil, as shown on the right-hand side of Figure 1. The United States is home to most known shale oil reserves, although countries like Australia, Brazil, Canada, and Russia are potentially endowed as well. The *shale oil revolution* is a main driver for the price-drop: its quick expansion led to an excess supply of crude oil that, in turn, put downward pressure on prices. This is what basic microeconomics suggests. However, as Figure 1 depicts, the expansion of US capacities was an almost smooth development over the years. Prices, in turn, exhibit an almost ad-hoc collapse such that identifying shale oil as the sole factor of the developments is economically implausible: It would require prices to react sudden and with a lag of multiple years. Baumeister and Kilian (2016) emphasise, based on an econometric analysis, that the price drop is a composite effect of positive supply shocks, negative demand shocks, and a shock in price expectations; however, they see demand changes as the main driver behind the price fall, with unexpected supply increases only influencing prices prior to 2014.

Additionally, a number of other influential factors are identified in the literature. Ambiguous results have been found regarding the influence of financial speculation: While Husain et al. (2015) reject this factor specifically, Fantazzini (2016) find evidence for the presence of a negative financial bubble. The appreciation of the US-Dollar might have been another factor (Tokic, 2015); although some studies (Alquist et al., 2013;

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Coudert and Mignon, 2016) fail to confirm significance or report ambiguities with respect to the direction of the currency effect over time.

Dale (2016) describes the establishment of what he calls the *new economics of oil*. He links the developments to fundamental changes in oil market rules: Crude oil has become virtually non-exhaustible (and is priced as such) due to changed market conditions (tight climate policies, extensive discoveries of new oil fields, maturity of renewable technologies); the direction of global crude flows has changed eastwards, which leads to market lags, partially because of a rigid downstream industry; the global crude supply curve has become flatter due to quickly reacting shale oil; and – even historically – OPEC has only been able to counter temporary shocks, never structural ones.

The political risks of OPEC states has a strong positive effect on energy security and prices (Brown and Huntington, 2017; Chen et al., 2016). Hence, the relative stabilisation of Middle Eastern geopolitics influenced the developments. Needless to say, the region is far from being stable or even safe, but the decline in Iraqi oil production has been far less than previously expected, Libya even expanded its production in 2014 (despite internal conflicts), and improved relations between Iran and the West stabilised Iran's output (Arezki and Blanchard, 2014; Baffes et al., 2015).

No doubt, all these factors have influenced the price trajectory and are a solid base for a convincing framework. However, the core question of why did OPEC not intervene in order to increase oil prices by announcing a cut in production remains unanswered.

2.2 Understanding and modelling OPEC

Starting in June 2014, oil prices started declining moderately. However, following the OPEC meeting on November 27, 2014 and its announcement that there would be no production cut, oil prices dropped by more than 30 USD / bbl within two months. In December 2015, following a year of low oil prices, OPEC decided to continue production as before, implying an extension of de-facto suspension of production ceiling. Starting in early 2016, OPEC and Russia began negotiating a deal for production cuts. A final deal involving Iran was achieved in December 2016.

There is no consensus regarding the actual reason behind OPEC's initial decision to not cut production. However, explanations given by analysists fall into three main categories:

- OPEC flooded the market with crude in an attempt to defend its market share and to drive out shale producers (Behar and Ritz, 2017; Brown and Huntington, 2017; Coy, 2015; Gause, 2015; Mănescu and Nuño, 2015);
- shale oil has taken OPEC's role as the swing producer and its members were forced to accept low prices (Baffes et al., 2015; Baumeister and Kilian, 2016; Dale, 2016; Kaletsky, 2015; The Economist, 2015); or
- uncertainty about shale oil behaviour made it necessary to test its resilience (Fattouh et al., 2016; Huppmann and Livingston, 2015).

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The first explanation corresponds to the basic idea of a standard market entry game: In a dynamic environment, if a market is contested by a new player, it may be rational for the incumbent firm to enforce a downward-pressure on prices in order to drive out the contestant, despite short-run losses for the incumbent. Behar and Ritz (2017) construct an algebraic framework with numerical computation. They show that flooding the market becomes the dominant strategy when shale supply and costs are high, non-OPEC capacities are large, and OPEC collusion as well as market demand are low; this has had been the case post-2014. Notably, the algebraic analysis reveals discontinuous best-responses. This means that a switch to the flooding strategy occurs when parameter thresholds are crossed, which is why market prices may jump as a response to even small parameter shocks. However, for the market entry argument to work, the incumbent's threat requires (i) credibility, (ii) effectiveness, and, at a minimum, (iii) temporal sustainability.

The second major category of literature claims that these conditions do not hold and that OPEC had to accept the presence and dominance of US shale oil. The quick expansion of shale resulted in a new balance of power in the market: The quick responsiveness of shale oil and its vast capacities, even at low prices, create a competitive environment. Any quantity withhold by OPEC is immediately substituted with shale, such that OPEC's decision was not a strategic one but rather the rules of competition left it no other choice. Baffes et al. (2015, p. 14) note that OPEC's decision to freeze output, "implies that OPEC will no longer act as the swing oil producer [and that] . . . marginal cost of unconventional oil producers may play this role."

Lastly, a possible third explanation is that OPEC was driven by uncertainty and a desire for industry consolidation. Huppmann and Livingston (2015) describe, in addition to the possibility of multiple equilibria in the market, that a pragmatic OPEC most likely attempted to gain crucial information regarding shale's performance in lower price ranges. Fattouh et al. (2016) express this argument in a more formal way, showing with a parametrised static game under uncertainty that, for a Saudi Arabia without sufficient knowledge about US shale elasticity, it is rational not to cut output, due to strict dominance of the corresponding strategy. Hence, Saudi Arabia had a large incentive to learn which game it is playing.

The actual nature of OPEC and its objectives have been a topic of discussions ever since the organisation's establishment. While some argue strictly that OPEC does not show cartelisation behaviour and should not be regarded as a such (Colgan, 2014; Kisswani, 2016; Plaut, 1981; Reynolds and Pippenger, 2010), others acknowledge OPEC's nature as a cartel but with limited collusion and prices below perfect cartelisation (Almoguera et al., 2011; Huppmann and Holz, 2012; Okullo and Reynès, 2016). Domestic oil dependency and the role of oil for the international economy further complicate this debate by adding other possible objectives regarding geopolitics, welfare, and domestic stability to profit maximisation (Hochman and Zilberman, 2015; Kisswani, 2014; Schwarz, 2008). The same applies to non-monotonicities such as behaviour and effectiveness differing with the direction of price changes (Alkhathlan et al., 2014; Loutia et al., 2016)

Obviously, the complicated, unclear nature of OPEC is a central challenge for modellers, who have to determine strategic objectives and the role of competition in the market. Over the last decades, virtually every possible setup has been applied, ranging from competitive setups to unequally distributed market

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power (for an overview on the different approaches, see e.g. Al-Qahtani et al. (2008)). Finally, Fattouh and Mahadeva (2013) offer a dismal outlook in this regards: OPEC's frequently changing objectives and politics make its behaviour time-variant such that a unified modelling approach is prone to fail.

3. The Model

3.1 Structure and approach

The framework is a so-called bathtub (or also pool) model. The term refers to all crude oil supply, regardless of origin or quality, being classified as one homogeneous good and facing a unified, global demand. Despite a general empirical indication for the bathtub market (Bachmeier and Griffin, 2006; Griffin, 2015; Gülen, 1999), it does not reflect the complicated, multi-staged, and spatially diversified reality of crude oil business adequately. First, crude is classified, traded, and priced according to its characteristics that determine processing and refining; the most important indicator for this is API gravity. Moreover, refining facilities differ between various input types of crude oil, such that each refinery can only process a limited subset of crudes. Therefore, spatial conditions may have crucial influence on supply and demand, as emphasised for instance by Langer et al. (2016).

As explained before, the complex and time-variant nature of OPEC and its objectives make it virtually impossible to construct realistic, consistent models of the oil market over a large time horizon. Moreover, data scarcity is a severe issue when fitting parameters for numerical models of the oil sector. Therefore, in this study, I do not attempt to construct a picture of the oil market that is necessarily accurate but rather one that reflects a stylised, simplified market and that is tailored to address the following question: Can low-price market outcomes post-2014 be explained by (short-term) profit maximisation, under whichever competition setup?

For this, suppliers are assumed to maximise short-term profits under full information with temporal dichotomy, i.e. they maximise their profit in every single period individually, given production capacities and knowledge about each other's costs and capacities. Hence, the model does not incorporate dynamic or signalling-based strategic behaviour. Although, at a first glimpse, this assumption seems to be inconsistent with the research question itself, it is both reasonable under usual market circumstances and important for accessing the issue. First, in *normal* times, crude oil producers have only little incentive to withhold (larger) quantities but they will usually provide whatever yields (short-term) profits, due to particularly high initial investments albeit comparatively low running costs and long project durations as they are typical for conventional crude oil. Since the market is dominated by large state companies and multinationals, it is reasonable to assume that – as a result of experience and research – they have profound beliefs about each other's parameters (i.e. production costs and capacities). Most importantly, however, I use this assumption similar to a testable hypothesis: It allows me to answer whether market developments are actually consistent with *standard* static competition, or whether they arise most plausibly from dynamic calculus or information-revealing behaviour. In other words, the results' ability to explain actual prices is used to (possibly) reject short-term profit maximisation as the underlying market behaviour.

Basically, I assume a common partial equilibrium model with heterogeneous suppliers in static quantity competition under capacity restrictions. Competition takes place in quantities for both technical considerations (Bertrand's paradox) and in accordance with the practice of crude oil business: Suppliers decide about the amount of oil to extract, while prices are determined in market equilibrium. Moreover, it reflects OPEC's practice of setting quotas as output "recommendations" for its members. Formally,

$$\max_{q_{it}} \{p_t(\cdot)q_{it} - C_{it}(q_{it}) \mid q^{S}_{-it}\} \; \forall i, t,$$

where p is the market price, q is a supplied quantity, and C are production costs. The subscripts i and t refer to the set of different suppliers and time periods respectively. Appendix A1 contains a table of notation as well as an overview of the algebraic relationships. In the different competition setups, the argument of the price function (an exogenous market clearing variable versus a demand function) and any knowledge / anticipation of the others' quantities already produced / to be produced (q^{S}_{-it}) are varied.

I assume a demand function that is linear in the output of crude oil. Periodical slope and intercept are fitted accordingly as a linear extrapolation from an estimate for the short-term elasticity of demand and actually observed market prices and quantities. Production costs are specified as proposed by Golombek et al. (1995), i.e. a producer-specific cost function that consists of a linear, a quadratic, and a logarithmic term. The latter diverges to infinity as a producer approaches their capacity limit. This setup allows for a marginal cost behaviour that matches the market's technological constraints: For low and intermediate levels of output (in terms of production capacity), the additional costs of extracting a further barrel of oil rise only moderately. When reaching the production limit, however, the costs for additional oil extraction rise sharply. Moreover, in terms of modelling, this term provides a cost-based capacity constraint, since a profit-maximising producer will not incur these costs.

Lastly, a slight relaxation to the strong assumption of homogenous crude oil is made. Quality differences are relevant for refineries (i.e. on the demand-side), since crudes of higher quality yield higher prices. However, adjusting demand is problematic in a pool model: It complicates the fitting of a unified demand curve significantly. Instead, another approach is to vary producer-specific costs: Each producers' costs are multiplied with the quality adjustment parameter η_i, which penalises (favours) suppliers of crude oils with lower (higher) quality with higher (lower) costs to maintain parity with a reference oil. Hence, heterogeneity is approximated by normalising crudes to a reference quality. This is to adjust a producer's profit-margin for quality not via revenues but expenditures, leaving decision-making conceptually unaffected.

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3.2 Competition setups

Quarterly equilibria from 2011Q4 through 2015Q4 are computed for five different competition setups. Table 1 provides an overview of the different specifications. Mathematical problem formulation is explained in the next subsection; the complete model formulation is presented in Appendix A1.

In perfect competition, producers ignore their effect on the price and do not engage in strategic decision making; instead they maximise their profits in anticipation of a given price. This leads to a price-setting rule in which producers supply until reaching their marginal costs. Hence, prices are only driven by production technology, which is why perfect competition constructs a lower bound for the prices in an environment free of market power. Formally, the setup's maximisation problem reads:

$$\max_{q_{it}} \{p_t q_{it} - \eta_{jt} C_{it}(q_{it}) \mid p_t \; given\} \; \forall i \in I, \forall t \in t \quad (1)$$

In Cournot competition, all suppliers decide about their quantities simultaneously and in anticipation of each other's decision. This means that producers take into account their choices' effect on the market price. The result is a Nash equilibrium, implying that all suppliers provide quantities such that no one has a unilateral incentive to change their output. The corresponding maximisation problem is given by:

$$\max_{q_{it}} \{p_t(\cdot) q_{it} - \eta_{jt} C_{it}(q_{it})\} \; \forall i \in I, \forall t \in T \quad (2)$$

However, more sophisticated market structures might be present, especially due to an uneven distribution of market power or sequential decision-making. In the prominent Stackelberg game, one firm precedes another one by making a credible commitment to a decision, anticipating the reaction of the following firm. The latter decides in knowledge of the leader's binding choice. In general, such a structure is desirable for the leader since it involves a so-called first-mover advantage, i.e. the leader's market power enables him to yield larger profits than in the case of simultaneous decision-making. A general formulation of this game with multiple players is given by

$$\max_{\substack{q_{jt} \\ \forall j \in J}} \left\{ p_t(\cdot) \sum\nolimits_{j \in J} q_{jt} - \sum\nolimits_{j \in J} \left[\eta_{jt} C_{jt}(q_{jt})\right] \mid q_{kt}^R \; \forall k \in K \right\} \forall t \in T \quad (3)$$

$$s.t. \max_{q_{kt}} \{p_t(\cdot) q_{kt} - \eta_{kt} C_{kt}(q_{kt}) \mid q_{jt} \; \forall j \in J\} \forall k \in K, \forall t \in T \quad (4)$$

where $j \in J$ refers to the set of Stackelberg leaders and $k \in K$ denotes the set of followers. q_{kt}^R implies the anticipated reaction of the followers. Such a structure could be attributed to Saudi Arabia alone, or OPEC as a whole. Through the credible announcement of production quotas, non-OPEC suppliers choose their quantities in knowledge of OPEC target production. Concerning the followers, two different structures are possible: Either the followers themselves are endowed with market power and engage in Cournot-style competition in the second stage; or it could be the case that the followers behave competitively and supply the residual demand. The latter is called a *competitive fringe*. Three setups of this kind are used: First, in the

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"United OPEC" setup, I assume an OPEC multi-plant supplier leading the market, i.e. OPEC acting as a single entity and maximising their joint profit. This setup constructs an upper-level benchmark: The resulting market outcome involves the highest exercise of OPEC market power possible. For the second stage, I assume Cournot competition. Secondly, I choose two variations of Saudi Arabia leading the market solely, first against Cournot followers and second against a competitive fringe.

3.3 Data and numerical implementation

The scarcity of reliable, disaggregated data for the crude oil sector is a central challenge when constructing numerical models. The issue cannot be mitigated entirely, but estimations and data choice are carefully made.

The data incorporates 29 suppliers (including all OPEC members), accounting for 94.4% of the global crude oil production in mid-2013 (IEA). Despite the large market share included, demand is adjusted by a parallel shift to account for the demand lost by omitting minor producers; otherwise, upward-biased prices might be a result. Production data is taken exclusively from IEA's Oil, Gas, Coal, and Electricity Quarterly Statistics (from 2013Q3 to 2016Q4). In line with multiple recent estimations (Caldara et al., 2016; Javan and Zahran, 2015), short-term price elasticity of demand is set equal to -0.1.

I calculate capacity data using two different methods. For OPEC members, IEA publishes estimates on crude oil production capacities in their Oil Medium-Term Market Reports. Final quarterly data is obtained using a cubic spline interpolation of IEA's annual data. For non-OPEC suppliers, country-level capacity data on a global scale with public access is unavailable. Thus, their capacities are set based on actual production, assuming that 97% of the available capacity is used in each period. This approach is common for country-level models in the crude oil sector (e.g. Behar and Ritz (2017)) and follows a simple rationale already introduced: (Conventional) projects are characterised by high initial costs, a long project lifetime, and relatively low running costs. Hence, outside of OPEC, suppliers have no official spare capacities and hardly any incentive to have such (Aguilera and Radetzki, 2015).

Data on production costs is taken from Huppmann and Holz (2012), Huppmann and Egging (2014), and Langer et al. (2016). Costs account for production only, meaning that capital investment is not included, and are assumed to not change over time: As pointed out by Aguilera and Radetzki (2015) and Aguilera (2014), production cost behaviour over time tends to show cyclic behaviour instead of monotonically increasing behaviour, and Toews and Naumov (2015) estimate that cost shocks have had no significant effects on oil prices. Nevertheless, constant costs throughout all periods bear the problem of not capturing a potential cost decline in shale oil (related to increased efficiency). To provide a workaround despite data scarcity, a sensitivity analysis with respect to costs is included in Appendix A4.

For the quality adjustment parameter, I apply the following strategy: First, an OLS regression of a log-log model of prices for different crude oils and the crudes' API gravity (U.S. Department of Energy) is performed, including dummies for temporal variation. Secondly, a virtual average crude (precisely, its API) is determined

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for every supplier, based on differentiated firm-level production data from the Oil & Gas Journal and EIA. The quality adjustment index is then finally obtained as the inverse ratio of model-fitted prices for the virtual averages and WTI. Estimated adjustments range between roughly 0.97 and 1.13 with most (large) producers between unity and 1.06.

All models are implemented in the software package GAMS. Cournot and perfect competition setups are formulated as mixed complementarity problems (MCPs) and solved via PATH solver (Ferris and Munson, 2000). The Stackelberg setups are formulated as mathematical problems under equilibrium constraints (MPECs) and are implemented as mixed integer non-linear problems (MINLPs) via disjoint constraints (Fortuny-Amat and McCarl, 1981). As solvers, I use both BONMIN (Bonami et al., 2008) and Couenne (Belotti, 2009). Cournot and perfect competition models behave regularly and can be solved quickly. Solving the Stackelberg models, however, proves more difficult due to non-convexities and corner solutions. The latter are the result of a high concentration in production capacities (Gini coefficient: 0.505), since only five countries account for more than 50% of global production (in descending order, Saudi Arabia, Russia, USA, China, and Iraq). In general, equilibria in Stackelberg are non-unique and are often associated with entirely different outcomes. In each case, I only report the equilibrium with the highest profit for the Stackelberg leader.

4 Results

4.1 Price trajectories and goodness of fit

Figure 2 displays the resulting price trajectories for the different competition setups in contrast to the actual prices observed. Throughout the first part (until 2014Q3), computed prices form a channel around actual prices. As expected and intended, perfect competition prices are lower than actual prices and notably stable over time. They mark the lower benchmark of marginal costs. The two Saudi Arabia cases with fringe and Cournot followers, respectively, define a price corridor around actual prices with the former continuously below and the latter continuously above. Cournot competition leads to prices significantly exceeding the actual values, although the United OPEC case returns prices that overshoot actual prices by more than 200% in some periods.

Overall, given the significant simplifications assumed, the model fit is reasonable (Appendix A2 contains a quantitative evaluation of the goodness of fit). However, after entering the second part (from 2014Q3 onward), actual prices sink to a level that is not explained by any of the setups. Notably, this includes perfect competition, implying that prices sink below marginal costs for some suppliers. Hence, the modelling approach is inherently unable to explain prices following the drop. This confirms that short-term profit maximisation fails to explain low oil prices. As a result, given the model's parameters, I can reject that the price drop is a result of static competition under full information. This leads to the intermediate conclusion that the price drop originates from non-static (i.e. dynamic or price-revealing) behaviour.

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Remarkably, only Russia, Saudi Arabia, and the US experience major variations in quantities (Appendix A3) across the different setups. The additional supply relative to actual prices mostly originates from Russia. The result of actual prices sinking below marginal costs is robust with variations in the cost parameters by more than 30%, such that potentially overestimated costs are unlikely to be the driving force (Appendix A4).

4.2 United OPEC and the price mechanism

Analysing the United OPEC setup is beneficial for two reasons. First, it provides a particularly interesting counterfactual: Imagine OPEC was behaving like a joint, world-leading supplier similar to a united country. Such an entity would have been able to drive crude oil prices above 200 USD / bbl for short-term profit maximisation. Obviously, this is realistic by no means since the setup disregards any kind of individual incentive constraints for the cartel's members and, thus, it does not regard possible (and in this case unilaterally rational) defections from the collusion agreement. The setup does not treat OPEC as a number of suppliers with different aims and *egoist* strategies, which contradict large sacrifices by a single supplier for the better of the whole.

This, in turn, leads to the second benefit from studying this example: The United OPEC scenario explains substitutions and price mechanisms in the market. Figure 3 depicts OPEC profits and supply in 2015Q1. Obviously, the joint OPEC profit in United OPEC exceeds profits from Cournot equilibria. However, Saudi Arabia's optimal profit shrinks considerably with United OPEC while the others' profits rise. The underlying strategy is as follows: Market leader Saudi Arabia is able to cut approximately half of its production, which elevates the price. Although the kingdom's profits diminish due to the large reduction, the resulting value effect via other OPEC members' production outweighs the loss in Saudi Arabian profit, such that the joint net profit of a unilateral cut is positive.

As previously noted, such a strategy is not incentive compatible in a real-world environment. Still, beyond being an interesting counterfactual, it reveals a major obstacle for OPEC: Given the large expansion of Russian and US production capacities, a modest production cut will only cause a gentle price response, since much of the quantity offset will be substituted by non-OPEC suppliers. To cause prices to rise above 100 USD / bbl, Saudi Arabia would need to announce a production cut that leaves itself worse off than in a nearly competitive equilibrium.

5 Discussion

The modelling results have shown that short-term profit maximisation is unable to explain low oil prices: While the model has a reasonably good performance before the price-drop, prices after late 2014 were even below results for perfect competition. Hence, model results suggest that some suppliers were driven below marginal costs and voluntarily accepted short-term losses, in particular the US and Russia. Moreover, along the price drop, revenues of OPEC members shrank considerably. This supports the view that OPEC has not

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switched to competitive behaviour, but that the price drop is a result of an exercise of market power in the presence of rigid supply.

However, how can this finding be combined with the fact that an agreement to cut production has been reached in late 2016, supposedly abandoning this strategy? The following subsections elaborate on this question by analysing strategies for OPEC and the Kingdom of Saudi Arabia as its dominant actor, the performance of US shale, the influence of domestic politics, and, lastly, the role of Russia.

5.1 Saudi calculus: market share or revenue?

The decision-making process of Saudi Arabia can be characterised by a simple trade-off between present revenues and market-shares (see Fattouh et al. (2016) for an extensive discussion). Given fixed technology and investment decisions in the short-run, profit maximisation largely amounts to maximising revenues, given the often-low operational costs of Saudi Arabia and other OPEC producers. As such, generating higher revenues might have required reduced production and higher prices, as the model results show with the outcomes of short-term profit maximisation.

However, securing long-run profits may have rather required to defend market shares, i.e. to continue to supply even under low prices to decrease the influence of emerging shale oil and to hedge against technological innovation on either supply or demand side. Incentivised by high prices, shale technology has developed quickly, and similar developments have occurred on the demand side by cost-declines in renewables, increased energy efficiency, and substituting technologies. Previous fears of *peak oil* have replaced with concerns about pe*ak demand*, as also tightening climate policies may shift an even larger share of the primary energy mix away from oil. As such, low prices could – in principle – both secure market shares by driving out shale and cause a decelerated diffusion of renewable energies and alternative technologies, implying finally larger profits in the long run.

To some extent, similarities to Saudi Arabia's behaviour during the 1980s can be spotted. At that time, during the oil price spike, OPEC members broadly cheated on production quotas in order to exploit high prices, while western importers sought to decrease their dependency on oil imports. As Richards and Waterbury (2009) note, the subsequent flooding of the market by Saudi Arabia, which led to a significant price drop, contained three central messages: Other OPEC members should stop cheating, non-OPEC members should understand that Saudi Arabia has much more endurance in this game, and oil importers should not watch out for alternative technologies since oil can easily drive them out of business.

Moreover, crude is (at least believed to be) an instrument for geopolitics. Oil is an essential input for the current primary energy mix, while major industries and transport depend on it. Controlling a significant amount of both production and reserves inherently endows a supplier with political power. For a long time, this has secured Saudi Arabia's political status in the world and, in particular, its relationship with the US (Krane, 2015). Hence, a new entrant in the market is not only a market contestant but also a political one, and the kingdom defending its market share means not only it is defending future rents but also its future political influence.

However, how much weight does Saudi Arabia actually assign to market-shares and geopolitics in the oil trade-off? Not much, according to Fattouh et al. (2016). Indeed, the decision may be taken by economic constraints more than political will. Regardless of any efforts to diversify a future Saudi economy, presently it is dependent on oil revenues (Albassam, 2015; Cherif and Hasanov, 2014). As the model has shown, the price trajectory was considerably below short-term equilibria, hinting at the decline in revenues. As Nusair (2016) estimates, Gulf Cooperation Council GDPs are closely correlated with oil price movements, although the strength of the effect is asymmetric with respect to the direction of price movements. Mohaddes and Raissi (2016) estimate an average 2.14% decline in GDP for Gulf Cooperation Council states as a result of the shale oil revolution.

Low prices immediately hit the fiscal state of oil dependent economies. Fiscal breakeven prices of crude oil are rarely below 80 USD / bbl, and in the case of Saudi Arabia it was around 100 USD / bbl in 2014 (IMF). The consequence was a fiscal deficit of almost 20%. As a result, economic growth stagnated and, as part of austerity measures, project funding and wages in the public sector were cut, energy prices increased, and various taxes have been issued. For Middle Eastern economies that, in turn, broadly depend on government spending to finance implicit social contracts in the form of so-called authoritarian bargains (Assaad, 2014), losing the grip on oil revenues can easily cause unrest and bear a danger to the state itself (Ansari, 2016). A glimpse of the latter was visible after a Saudi-Arabian increase in water prices was introduced and the respective minister had to be replaced following public complaints.

Another point worth considering is the moral hazard Saudi Arabia is facing. Both OPEC and non-OPEC producers wanted Saudi Arabia to cut production after the price drop; but it quickly realised that such a cut would not necessarily be actively supported by other major suppliers such as Russia and Iran (Fattouh and Sen, 2015; Henderson and Fattouh, 2016). Even if such a unilateral cut was in Saudi Arabia's interest, being a long-time guardian of the oil market at its own expenses does surely not, since it would only encourage other suppliers to expand their capacities even more.

The intense struggles throughout 2016 to reach the final deal show that missing coordination had been a central issue: Despite promising advances at the Doha meeting in April, there was still no deal by August, when Iran refused to be part of it and the Saudi Arabian delegates reacted by withdrawing from the planned agreement. Only after Iran finally agreed to participate, the agreement was reached in December.

Although Saudi Arabian oil politics might be questionable, it is inaccurate and wrong to claim their actions had admitted an "implicit defeat" (Riedel, 2016) by "blinking" toward a deal (Blas and Smith, 2016), since it was in a severe "financial crisis" (Daiss, 2016). Instead, as also confirmed by Fattouh and Sen (2016), the kingdom had insisted on certain points, mainly on not rebalancing the market unilaterally and demanding an increase in own revenues with any proposed action. Such targets are perfectly rational from both a static and a dynamic perspective, as supported by modelling results for the United OPEC scenario. Also, in many regards, Saudi Arabia has been better prepared for low prices than others with large foreign reserves and still relatively low public debt (IMF).

Low prices can even be interpreted as a welcomed support for Crown Prince Mohamed bin Salman's Vision 2030 , which sees the country as an advanced, diversified economy with a strengthened private sector that is much less dependent on oil. Krane (2015) also sees a shift in Saudi geopolitics itself: The attempt to increase domestic refining, usually known to yield only small profit margins, shows that Saudi Arabia is growing out of its role as the US's reliable oil supplier and trying to stimulate a further integration into the rest of the world. Huppmann and Livingston (2015) interpret increased Saudi activity in the refining industry as an attempt to climb up the value ladder of global petroleum.

5.2 Shale performance under price pressure

When analysing OPEC behaviour in the presence of shale, it should be clear that the organisation is facing "uncharted territory" (Fattouh and Sen, 2015) with shale oil, because it is structurally different from conventional oil. Conventional production projects typically last 30 years and the equity-financed investment is mostly undertaken by multinationals. Its cost structure is characterised by high capital costs but relatively low extraction costs. Shale oil, in contrast, involves lower investment relative to conventional oil, but higher production costs. The market is dominated by small, independent US firms; projects typically last one year or less, and the market is characterised by a high degree of financial leveraging. This, in turn, has strong consequences for the elasticity of supply; i.e. how quickly and strongly shale oil responds to changes in price.

As depicted in Figure 4, the price drop hit the US crude oil industry hard. The number of rigs started to decrease substantially in 2015, declining by more than half. Expansion in crude oil production also came to a halt, and output actually decreased. Between 2015 and early 2016, more than 50 oil and gas firms went bankrupt (Reuters). This was mostly a result of the different market structure: Independent, leveraged firms in a short-term business (high production in wells usually lasts far less than a year) with smaller budgets and heterogeneous well economics even within a single formation are cut off from their financial streams as soon as the price falls below the breakeven point. However, the final impact on the shale industry was still less than many analysts expected, and clearly did not meet OPEC hopes. Moreover, it is reasonable to assume that the fast responsiveness of shale works in both directions: in the case of a price surge, financing of new shale projects might be issued, and the rig count would increase again. Hence, shale oil might have created a long-term price ceiling for crude oil.

Another issue is the price channel for shale oil itself. Before the drop, virtually every researcher and market analyst estimated the production costs of shale oil as being between 50 and 100 USD / bbl (Aguilera and Radetzki, 2015; Brecha, 2012; Huppmann and Livingston, 2015; Livingston, 2014; The Economist, 2014). As we know today, this was an overestimation, since some shale firms were still able to supply at prices beyond 30 USD / bbl (although many were not). Kleinberg et al. (2016) emphasise, however, the impact of a combination of exogenous and endogenous dynamics that led not only to a decline in relevant breakeven levels but also to a shift in the binding breakeven point, allowing shale producers to compete in low-price environments. Wood Mackenzie sees shale breakeven beyond 40 USD / bbl. It is questionable as to whether OPEC and Saudi Arabia in particular have had perfect knowledge in this regard, and OPEC (2016) admits that shale resilience was above expectations.

5.3 A change in Saudi politics?

To correctly understand the shift in OPEC policy, one should take a look beyond time-consistent strategies and also consider the influence of domestic politics. Ali al-Naimi, the Saudi Arabian Minister of Petroleum and Mineral Resources from 1995 to early 2016, was reported to be the brain behind 2014's decision and supposedly managed to convince all other OPEC members to join him (The Wall Street Journal, 2015). In an interview after the relevant OPEC meeting, he explained his position clearly concerning the decision:

> *I will tell you why. … If I reduce, what happens to my market share? The price will go up and the Russians, the Brazilians, US shale oil producers will take my share. … It is also a defence of high efficiency producing countries, not only of market share. … That is the operative principle in all capitalist countries. … If the price falls, it falls, you cannot do anything about it. But if it goes down, others will be harmed greatly before we feel any pain. … I want to make one thing clear. It is unfair of you to ask OPEC to cut. We are the smallest producer. We produce less than 40% of global output. We are the most efficient producer. It is unbelievable after the analysis we carried out for us to cut. … Whether [the price] goes down to $20/B, $40/B, $50/B, $60/B, it is irrelevant." (MEES, 2014)*

In 2015, Mohammed al-Sabban, a former adviser to al-Naimi, was still quoted as saying: "His biggest move was the latest one of defending Saudi market share, and abandoning the OPEC swing role" (The Wall Street Journal, 2015). The image OPEC and al-Naimi in person wanted to convey is unambiguous, at least: OPEC accepts the US' invitation and is willing to enter a price war – no matter the cost. The cartel seems keen and determined to put *inefficient* suppliers out of business, and presents itself as being prepared for the storm. As detailed above, to some extent they had reason to believe so. Well-known, Middle Eastern oil is not only of decent quality but also has some of the lowest production costs globally. Gulf Cooperation Council countries, especially Saudi Arabia, had mostly low debt and high positions in foreign assets. And indeed, the number of shale rigs has declined quickly. However, defending market shares comes at a cost – costs that have proved unsustainable for some OPEC members. Saudi Arabia too has seen itself faced with fiscal hardship, given that the decline in shale was beyond hope.

Surprisingly, in early 2016, the kingdom decided to replace al-Nami with Khalid al-Falih as the minister for a newly founded composite Energy Ministry. In June, the new minister announced: "We will be very gentle in our approach and make sure we don't shock the market in any way. There is no reason to expect that Saudi Arabia is going to go on a flooding campaign" (Reuters, 2016). Was al-Naimi's resignation the death sentence for the limited success of his policy and his inheritor chosen to make a U-turn? Or has al-Falih continued the legacy of al-Nami, who resigned after landing his greatest coup by challenging the new entrants, defending Saudi market shares, and revealing shale's potential under pressure? For anyone outside the kingdom's government, the stories are nearly indistinguishable. Still, the coincidence makes it necessary

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to consider that the change in policy did not necessarily originate in a consistent plan but could also represent a change in personnel and strategy.

However, in reference to the points discussed above, ambiguity does not necessarily require a binary conclusion. A switch in policy – from flooding to cooperation – is obvious, but a change in the underlying principles is not. Al-Falih has been seeking a collusive agreement with major producers, but not at any cost. Throughout the negotiations, unilateral action has been rejected ("[Saudi Arabia] is not going to withdraw production to make way for others", The Telegraph (2016)), and low prices increase Al-Falih's bargaining power with Russia, Iran, and the rest of OPEC. Ultimately, the oil price dynamics of recent years might have revealed that Saudi Arabia should be interested in neither low nor unnecessarily high prices, since the latter increase incentives for new technologies and market entrants, which is why balancing the market around a moderate price level is in the kingdom's best interest.

5.4 The Russia puzzle

Yet, one puzzle remains from the model results. Remarkably, resulting quantities have shown that strategic substitution in the oil market takes place virtually between three players: Saudi Arabia, Russia, and the US. All other suppliers move in areas of their marginal cost functions that are still far below prices, so that no incentive is given to reduce production, and potential spare capacities are too low to change market results unilaterally. Yet, in almost all competition setups, model outcomes predict that Russian oil is produced above equilibrium values. In the second part, the outcomes even suggest that Russian output is on a level above marginal costs. In other words, the model suggests that Russia is voluntarily incurring losses for some of their sales.

How reasonable and realistic is this is implication? If nothing else, it is not impossible, and is even supported by some figures: Rystad Energy and Morgan Stanley Commodity Research Estimates note that Russian onshore field extraction costs can reach as much as 70 USD / bbl. A number of reasons can be found to explain the presumed Russian overproduction. First, Russian oil production is (mostly) conventional, and as such there is a typical lag between price movements and supply adjustment, due to conventionals' investment cycle (Fattouh, 2016). Multiple projects were initiated shortly before the price drop (Henderson and Grushevenko, 2017). Secondly, a market share argument similar to OPEC seems to be in place. As the Russian Energy Minister said, "[i]f we cut, the importer countries will increase their production and this will mean a loss of our niche market" (Bowler, 2015). Lastly, Russia has a state-led system of organising and taxing the oil sector that results in actual production decisions by extraction firms that do not depend on the nominal oil price itself but on a net producer price; and both differ substantially (Drebentsov, 2015). During the price drop, Russia widely profited from their reserve fund, which was dedicated for such events. However, low oil prices led to fiscal deficits, and the fund cannot sustain low oil prices for multiple years, which is why Russia was promoting the deal intensively (Henderson, 2016).

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6 Conclusion and Policy Recommendations

Huppmann and Holz (2015) explain that whether "shale oil investment [has] decrease[d], because OPEC strategically drove US producers out of the market; or [because] the current trend [has] just [been] a broader market adjustment . . . [e]mpirically, these two storylines are virtually indistinguishable.". This statement is true to the extent that a definite answer may never be found.

Still, this study has provided numerical evidence from an equilibrium model: Despite computing prices with a reasonable fit for high-price periods, the modelling approach, based on short-term profit maximisation, failed as a whole when it entered the low-price periods post 2014. This can be understood as evidence that low prices cannot result from static competition but have to arise from dynamic calculus or information games. In the wake of Saudi Arabian oil market politics and developments in shale oil, it turns out that the most convincing explanation for the model results is that OPEC attempted to defend its market share and to test for the elasticity of supply and survivability of shale in an uncertain environment.

Saudi Arabia, as OPEC's main actor, changed its approach when negotiating a deal with other OPEC members and Russia. However, in many regards, this change does not necessarily reflect a fundamental change in strategy. It might have been experience gained regarding the resilience of shale and its endurance under low prices that equipped the kingdom with both sufficient knowledge and leverage to reach an agreement that still adheres to a basic principle: Saudi Arabia refuses to undertake any unilateral action that would result in long-run moral hazard.

Besides that, other incentives may have led OPEC members to accept low prices: Advances in renewable energies, alternative technologies, energy efficiency, and climate change policies alongside vast oil discoveries have turned fears of peak oil into fears of peak demand. To some extent, a market-share strategy might even prove beneficial in political terms when it comes to reforming previously mismanaged economies and deepening a more balanced integration in global politics and value chains, despite the fiscal hardship involved. Still, it should be kept in mind that any such oil market policy is no first best but has the primary aim of damage control in the presence of shale oil.

Needless to say, the modelling approach is economically simple, and it requires numerous assumptions to work. It is true that the model cannot predict market outcomes for a precise matter, explain trade flows, or provide unambiguous insight into OPEC's system of collusion. However, the model provides a scientific approach for accessing some major questions in a counterfactual way. Shortcomings concerning the data used for fitting the model are not a problem specific to this study but a general one for all applications in the crude oil sector.

After the deal has (at least temporarily) brought prices back to more moderate levels, what will the oil market of the future look like, and which role will OPEC play in it? If it was not for global, fundamental shocks, it is unlikely that we would continue to see extraordinarily high prices. Supported by the model's results, decreased demand and excessively expanded, mostly non-OPEC capacities have created an environment of increased competition. High prices require fundamental production cuts (by Saudi Arabia), which are by no means feasible in the context of OPEC governments whose ultima ratio is not fraternity but competition.

Shale is here to stay. Still, along with other recent studies, e.g. Brown and Huntington (2017), Fattouh and Sen (2016), Hosseini and Shakouri (2016), Matsumoto and Voudouris (2015), and Van de Graaf (2017) I conclude that this does not nullify the importance of conventional producers or OPEC in particular. The price recovery in the wake of 2016's deal shows that market power is still a central variable and that OPEC remains a major force, although time-invariant policies on a national but also on an organisational level lead to frequent changes in the market reactions observed. Notably, neither OPEC nor innovating and climate-ambitious importers have reason to desire steep price developments in either direction, as high prices will incentivise further development and exploration of shale, whereas low prices will reduce OPEC profits as well the competitiveness of alternative technologies, hampering their diffusion. Hence, the presence of shale oil could have introduced a price corridor for OPEC to act in, thus achieving something the market has barely seen so far: stability.

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Appendix

A1 Model formulation

Table 2 gives an overview of the model notation. The Golombek et al. (1995) cost function is given by (5), and marginal costs by (6). Note that a numerical implementation usually requires the explicit formulation of a dedicated capacity constraint and a sufficient relaxation of the logarithmic term by an arbitrary small constant. Linear demand for each period is given by (7), and intercept and slope parameters are calculated according to (8) and (9) respectively. (10) is the capacity constraint.

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$$C_{it}(q_{it}) = \gamma_{1i} q_{it} + \gamma_{2i} q_{it}^2 - \gamma_{3i}(q_{it} - \kappa_{it})\left(\ln\left(1 - \frac{q_{it}}{\kappa_{it}}\right) - 1\right) \quad (5)$$

$$\Rightarrow MC_{it} \equiv \frac{\partial C_{it}}{\partial q_{it}} = \gamma_{1i} + 2\gamma_{2i} q_{it} - \gamma_{3i} \ln\left(1 - \frac{q_{it}}{\kappa_{it}}\right) \quad (6)$$

$$p_t = \beta_{1t} + \beta_{2t} \sum_{i \in I} q_{it} \quad (7)$$

$$\beta_{1t} = \varphi_t(1 - \varepsilon^{-1}) \quad (8)$$

$$\beta_{2t} = \varphi_t(\chi_t \varepsilon)^{-1} \quad (9)$$

$$q_{it} \leq \kappa_{it} \quad (10)$$

The perfect competition model is implemented as a MCP with the Karush–Kuhn–Tucker conditions (KKTs) of maximisation problem (1) subject to (10) and as well as (6) and (7). $\perp$ is the perp operator, which implies that either term has to strictly equal zero.

$$0 \leq p_t - \eta_{it} MC_{it} \perp \kappa_{it} - q_{it} \geq 0 \qquad \forall i \in I \quad \forall t \in T$$

$$MC_{it} = \gamma_{1i} + 2\gamma_{2i} q_{it} - \gamma_{3i} \ln\left(1 - \frac{q_{it}}{\kappa_{it}}\right) \qquad \forall i \in I \quad \forall t \in T$$

$$p_t = \beta_{1t} + \beta_{2t} \sum_{i \in I} q_{it} \qquad \forall t \in T$$

Cournot competition is implemented as a MCP as well, consisting of the KKTs of maximisation problem (2) as well as (6),(7), and (10).

$$0 \leq p_t - \eta_{it} MC_{it} - \tau_i \perp \kappa_{it} - q_{it} \geq 0 \qquad \forall i \in I \quad \forall t \in T$$

$$MC_{it} = \gamma_{1i} + 2\gamma_{2i} q_{it} - \gamma_{3i} \ln\left(1 - \frac{q_{it}}{\kappa_{it}}\right) \qquad \forall i \in I \quad \forall t \in T$$

$$p_t = \beta_{1t} + \beta_{2t} \sum_{i \in I} q_{it} \qquad \forall t \in T$$

All Stackelberg variations are implemented as MPECs via disjoint constraints. This implies the maximisation of (3) under the equilibrium conditions (5), (6), (7), and (10), the KKT of (4), and the two disjunctive constraints to enforce complementarity between the followers' marginal profits and their capacity constraints. The binary parameter f enables a generic notation for the Cournot follower ($f = 0$) and competitive fringe case ($f = 1$). r_{ik} is a binary variable and BIG an arbitrary, sufficiently large constant.

$$\max_{\substack{q_{jt} \\ \forall j \in J}} \left\{ p_t * \sum\nolimits_{j \in J} q_{jt} - \sum\nolimits_{j \in J} \left[\eta_{jt} C_{jt} + +\tau_j q_{jt} \right] \right\} \qquad \forall t \in T$$

$$C_{jt} = \gamma_{1i} q_{it} + \gamma_{2i} q_{it}^2 - \gamma_{3i} (q_{it} - \kappa_{it}) \left(\ln \left(1 - \frac{q_{it}}{\kappa_{it}} \right) - 1 \right) \qquad \forall j \in J \quad \forall t \in T$$

$$0 \leq p_t + (1 - f) \beta_{2t} q_{kt} - \eta_{kt} MC_{kt} \qquad \forall k \in K \quad \forall t \in T$$

$$MC_{kt} = \gamma_{1k} + 2\gamma_{2k} q_{kt} - \gamma_{3k} \ \ln \left(1 - \frac{q_{kt}}{\kappa_{kt}} \right) \qquad \forall k \in K \quad \forall t \in T$$

$$0 \leq \ \kappa_{it} - q_{it} \qquad \forall i \in I \quad \forall t \in T$$

$$p_t = \beta_{1t} + \beta_{2t} \sum\nolimits_{i \in I} q_{it} \qquad \forall t \in T$$

$$p_t + (1 - f) \beta_{2t} q_{kt} - \eta_{kt} MC_{kt} \leq r_{kt} BIG \qquad \forall k \in K \quad \forall t \in T$$

$$\kappa_{it} - q_{it} \leq (1 - r_{kt}) BIG \qquad \forall k \in K \quad \forall t \in T$$

A2 Model fit

Goodness of model fit in the different setups is measured with the *average relative modulus error* (ARME). This decision is based on two central reasons. First, the metric must be invariant to the direction of a deviation, which is ensured by the modulus operator. Second, any absolute measure (such as a mean squares formulation) suffers from the variation in actual values themselves, i.e. an absolute distance measure would weigh deviations in high-price periods relatively higher than deviations in low-price periods. However, due to the method for demand extrapolation, the magnitudes for all results move closely with actual prices over time. Therefore, a shrinkage of the absolute error during the low prices or a trajectory's direction cannot be interpreted as a better fit in comparison to the first period but as an endogenous effect. Hence, an adequate error metric has to lay equal weight on all periods. This is fulfilled by the ARME's normalisation on each period's price. Formally, the ARME of any setup s is computed as

$$ARME_s = \frac{1}{T} \sum\nolimits_{t=1}^{T} \frac{\left| p_{s,t} - p_{act,t} \right|}{p_{act,t}},$$

where $p_{s,t}$ and $p_{act,t}$ refer to the resulting price of setup s in period t and the actual price in period t respectively. $|\cdot|$ is the common modulus operator.

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Using the ARME criterion, the Saudi Arabia versus a competitive fringe setup proves best throughout both periods (see Table 3), followed by perfect competition and the Saudi Arabia Stackelberg against a Cournot market. Obviously, the worst performing setup is United OPEC. However, there are large differences between the first and the second part. While the best-fitting model performs well throughout both parts, perfect competition does not perform well in the first part but only in the second. Its low overall ARME is the result of perfect competition, having the lowest prices in the wake of the unexplainable prices post Q4 2014. It should not be understood that perfect competition was a good approach to model competition in the crude oil market. The Saudi-Stackelberg with the Cournot follower, and the Cournot setup itself in a similar fashion perform considerably worse in the second part than in the first, with their ARMEs more than double the size in the former

A3 Production quantities

Figure 5 shows actual and computed production capacities for the cases of 1st quarter 2013 and 1st quarter 2015 to include both a period of the first part and one of the second part. Spare capacities, shown in Figure 6, are defined as the difference between production and capacity limit and may provide a better illustration than production itself.

Actual spare capacities are mostly held by Saudi Arabia (KSA) and some other OPEC countries, with relatively small amounts held by non-OPEC suppliers. The best-performing Saudi Arabia versus Fringe setup involves slightly higher production in Q1 2013 and lower production in Q1 2015 relative to the actual case. In the former, the additional supply mostly originates from other OPEC members (which have no incentive to withhold any amount as part of the competitive fringe), while in the latter, Russia (RUS) and the US produce far less than is the actual case. This picture is consistent throughout all setups: in 2015, both suppliers seem to have supplied quantities beyond oligopolistic equilibria and – especially in the case of Russia – above marginal costs.

A4 Cost sensitivity analysis

A lack of adequate data is an omnipresent problem for research on crude oil markets. For this study, cost data is a central obstacle: The rejection of short-term profit maximisation as an assumption was based on actual prices falling below perfect competition levels, which are nothing but marginal costs for an interior optimum. To ensure the result's robustness, a sensitivity analysis with respect to production costs was conducted. Figure 7 displays the trajectories of actual prices and perfect competition under different cost specifications (original costs as well as 10%, 20%, and 30% overall cost reduction). In each of the control cases, the cost for all suppliers decreased by the respective percentage. Results in 3rd quarter 2015 can only be explained by perfect competition with costs as low as 30% below the cost data assumed. Actual prices from 4th quarter 2015 require an overestimation of production costs exceeding 40% to match perfect competition. Hence, the statement that oil prices sank below marginal costs proves robust with respect to large variations in cost parameters, strengthening the results and the intermediate conclusions.

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Figures

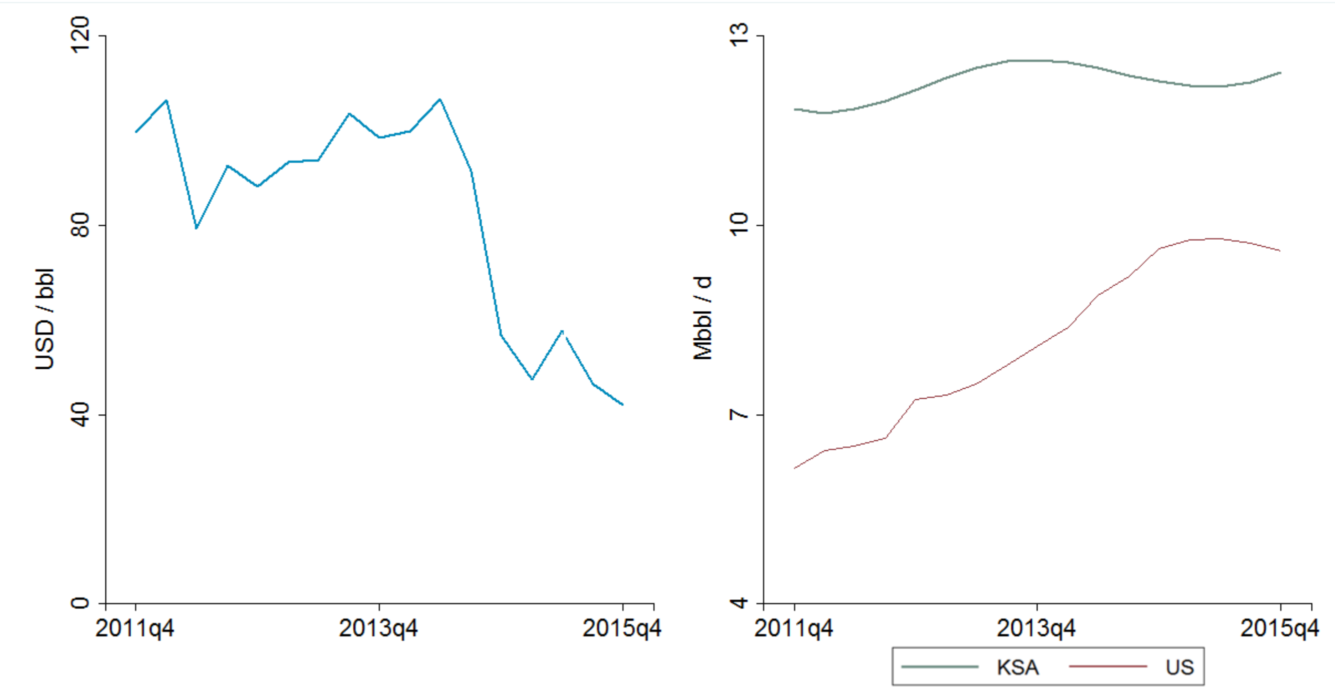

Figure 1: WTI crude oil price (left) and estimated production capacities of Saudi Arabia (KSA) and the US (right). Data: IEA, Reuters, own calculations

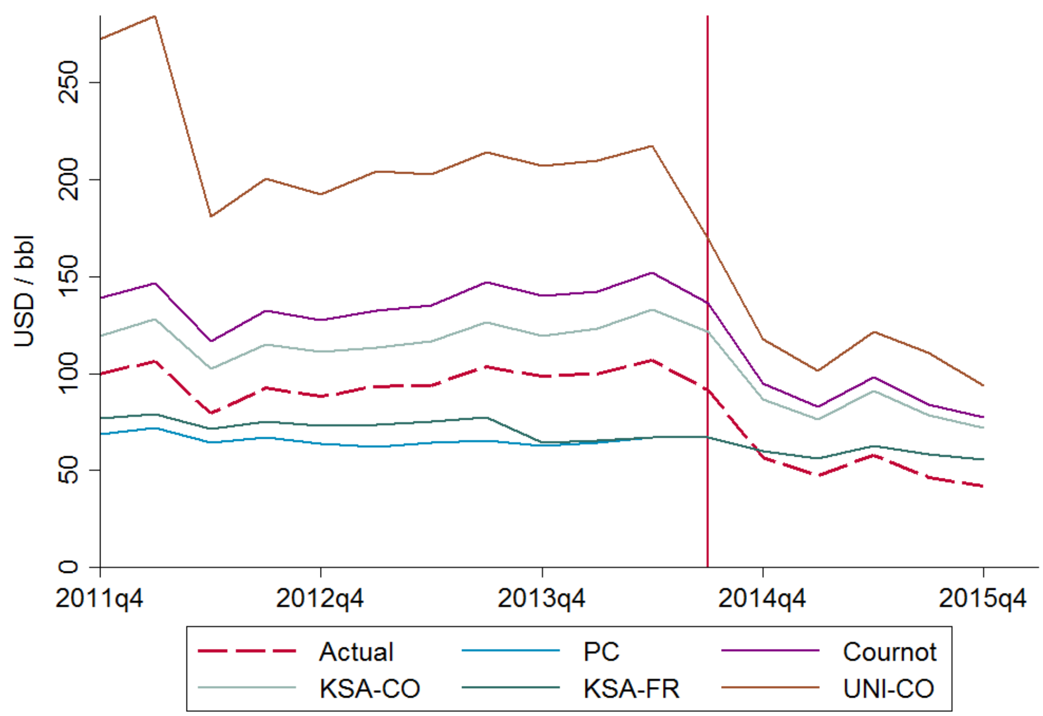

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Figure 2: Actual and computed price trajectories

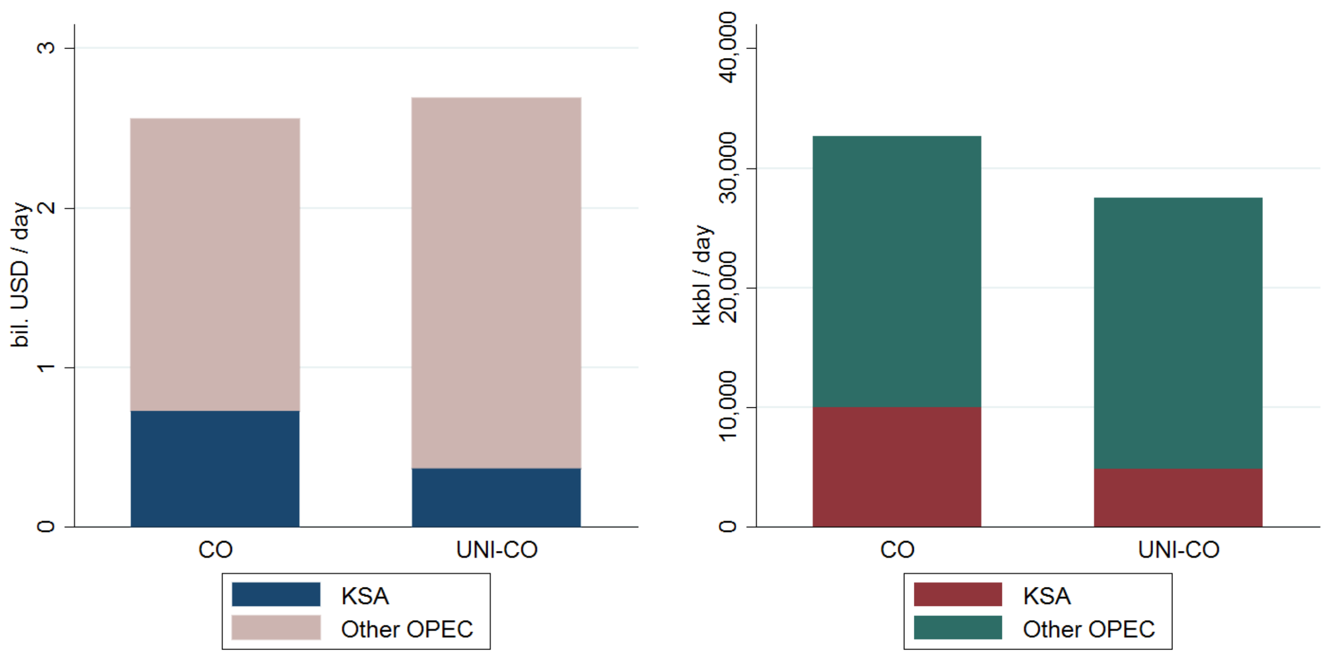

Figure 3: Computed profits (left) and production quantities (right) for the United OPEC setup in Q1 2015 by Saudi Ara-bia (KSA) and other OPEC members

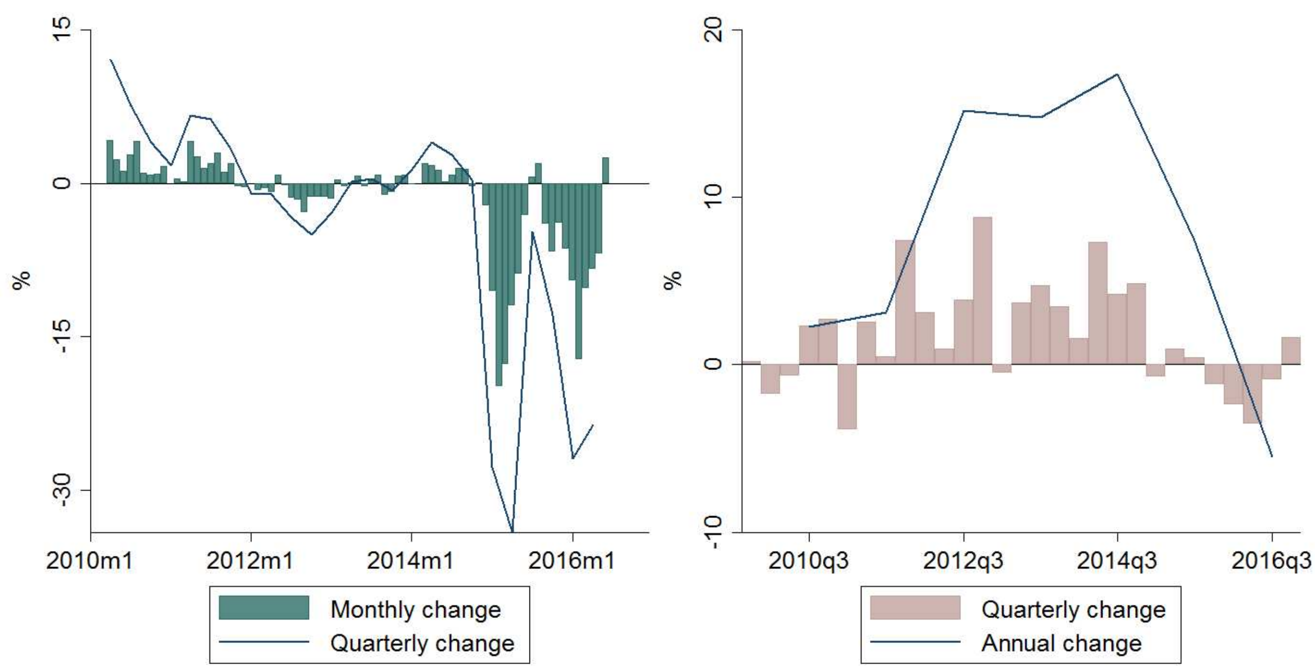

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Figure 4: Month-to-month and quarter-to-quarter changes in US rigs (left) and quarter-to-quarter and year-to-year changes in US daily crude oil production (right). Data: EIA

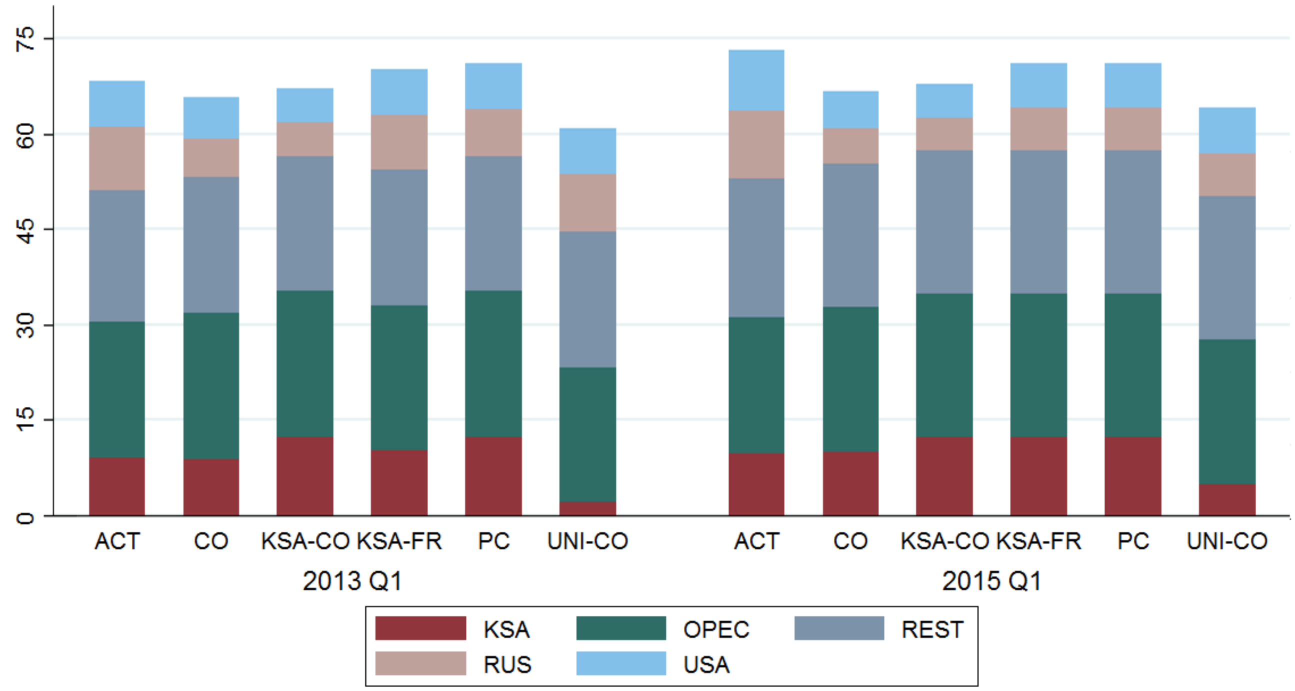

Figure 5: Actual and computed production quantities in Mbbl / day for Q1 2013 and Q1 2015

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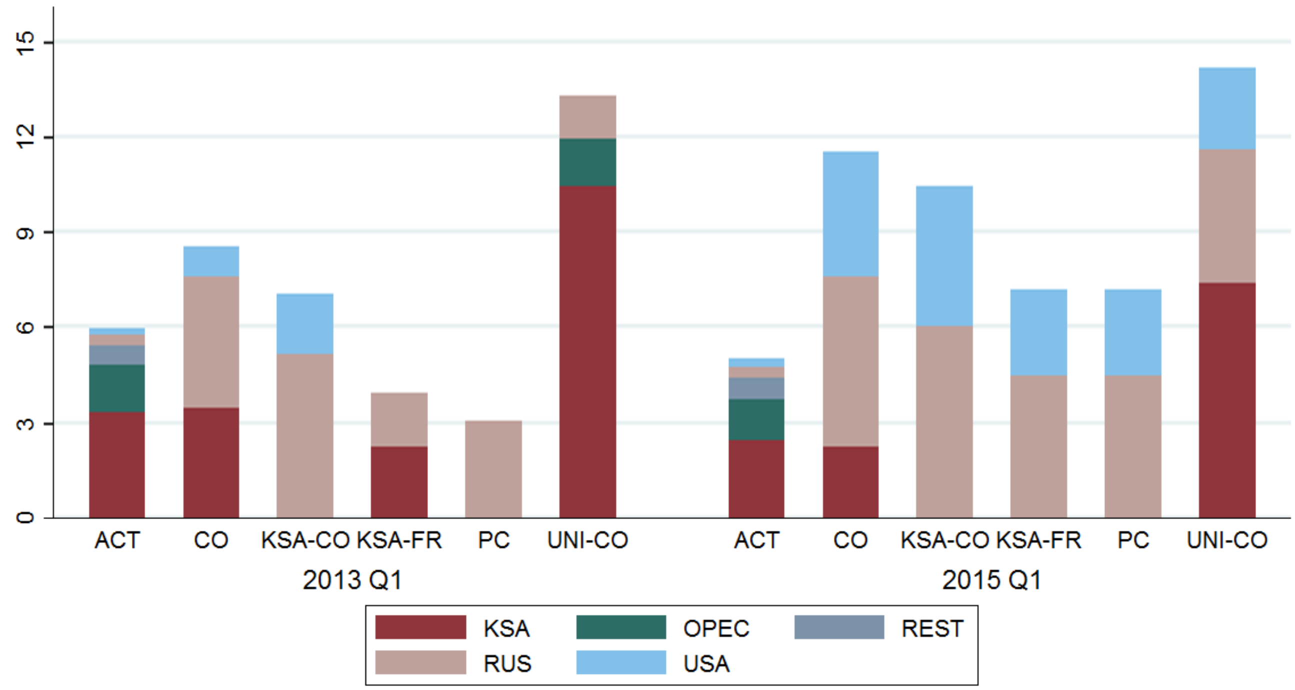

Figure 6: Actual and computed spare capacities in Mbbl / day for Q1 2013 and Q1 2015

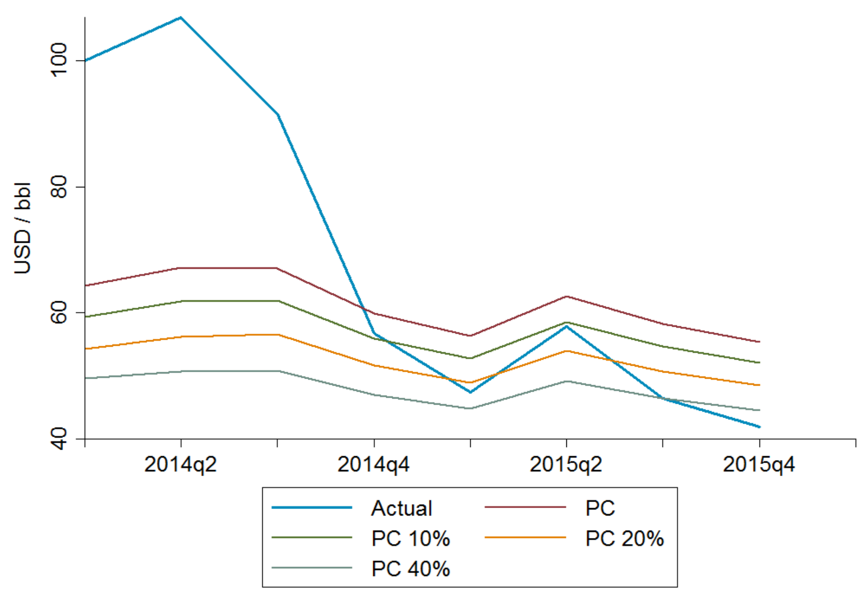

Figure 7: Robustness of perfect competition results with respect to cost variations (overall cost reductions in %)

Tables

Abbr.	Name	Description	Model
PC	Perfect competition	All suppliers decide simultaneously as price-takers	MCP
Cournot	Cornout	All suppliers decide simultaneously with equal market power	MCP
KSA-CO	Saudi Arabia – Cournot Stackelberg	Saudi Arabia decides unilaterally in a first stage; all other suppliers follow in a Cournot game	MPEC
KSA-FR	Saudi Arabia – Fringe Game	Saudi Arabia decides unilaterally in a first stage; all other suppliers form a competitive fringe	MPEC
UNI-CO	United OPEC – Cournot Stackelberg	OPEC behaves as a single entity and decides in a first stage; all other suppliers follow in a Cournot game	MPEC
ACT	Actual	The prices actually observed in reality	-

Table 1: Overview of the different competition setups

Set Indices	
$i \in I$	Crude oil producing countries
$j \in J \subseteq I$	Stackelberg leaders
$k \in K \subseteq I$	Stackelberg followers
$t \in T$	Time periods in quarterly steps from 4th quarter 2011 onwards
Parameters	
β_{1t}, β_{2t}	Demand parameters
ε	Price elasticity
φ_t	Observed actual price
χ_t	Observed actual quantity
$\gamma_{1i}, \gamma_{2i}, \gamma_{3i}$	Cost parameters
κ_{it}	Production capacity
η_i	Quality of oil index
Variables	
$p_t \in \mathbb{R}_0^+$	Market price in period t
$q_{it} \in \mathbb{R}_0^+$	Quantity supplied by producer i in period t

Table 2: Model notation

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ARME in %	**KSA-FR**	**PC**	**KSA-CO**	**Cournot**	**UNI-CO**
Overall	23	27	35	52	120
First period	25	31	24	43	121
Second period	18	18	63	75	119

Table 3: Goodness of fit according to average modulus error (ARME) criterion by competition setups and time (lower is better)