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Mothballing in a Duopoly: Evidence from a (Shale) Oil Market

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Summary

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Keywords: Crude Oil, Shale Oil, Mothballing, OPEC, Output Game

JEL Classification: L12, L71, Q41

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Mothballing in a Duopoly: Evidence from a (Shale) Oil Market

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Abstract

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1 Introduction

In applying a strategic mothballing framework to the (shale) oil industry, the contribution of this paper is both theoretical and practical. From a theoretical perspective the novelty is that we introduce the option to mothball in a duopolistic real options framework. Up until now, within the theory of real options mothballing occurs in monopoly models, as in Guerra et al. [2018] (see also [Dixit and Pindyck, 1994, Chapter 7]). We employ our newly obtained results to analyze the game between OPEC and shale oil producers, where, by enlarging production, OPEC could push shale oil producers in a mothballing state.

The combination of horizontal drilling and hydraulic fracturing used to extract crude oil and natural gas was developed in the 1970s (Mănescu and Nuño [2015]). It has grown dramatically over the last few years, resulting in a so-called "Shale Revolution". In 2013 the United States is estimated to have produced 3.5 mb/d of shale oil, which is three times higher than the amount produced in 2010 (Energy Information Administration [2014]). The level of US crude oil production reached almost that of Saudi Arabia and Russia in 2015 (Bataa and Park [2017]). Therefore, the first effect of the shale revolution is an increase of oil and gas supply, especially for the US. The second (indirect) effect is the 2014-2016 drop in crude oil prices (Ansari [2017])[1]. Given this increase of US oil supply and therewith, increasing competition in the oil market, the expected reaction of OPEC was a reduction of supply to maintain price and profit shares. However, surprisingly OPEC maintained stable production. An extensive market analysis is provided in the Appendix.

Analyzing this game between OPEC and the shale oil producers is important, because in general fluctuations of international crude oil prices have a strong impact (Chen et al. [2016]) on economic output (Wei et al. [2016], Wang and Zang [2014]), inflation and unemployment (Uri [1996], Du:), the stock market (Cong et al. [2008]) and fundamental industries (Jiao et al. [2012]). Evidence about direct strategic interactions between OPEC and the shale oil industry can for instance be found in the Economist Espresso from November 30, 2017[2]. There we read about an OPEC meeting in Vienna where it was stated that "soaring prices would further stimulate American shale production". One day later, the Economist Espresso from December 1, 2017[3] notes that "OPEC agreed to extend its oil production cut of 1.8m barrels per day by nine months, to the end of 2018. The cartel is walking a fine line in trying to draw global surpluses and nudge prices up without sparking new production by nimble American shale producers".

For a long time, theoretical papers have debated the competitive structure of the global oil market and the consequences on the formation of oil price. Researchers have wondered to what extent oil producers (economic agents) coordinate their production strategies (Geroski et al. [1987]). If the dynamics that describe the oil market can be represented by strategic balances ascribable to game theory, economic literature has wondered if the role of Saudi Arabia is that of a swing producer (Nakov and Nuno [2013]) and if OPEC acts as a cartel or participates in a game à la Stackelberg (Dahl [2004], Berg et al. [1997]). More recently theoretical frameworks have also considered the possibility that OPEC pursues different production strategies, depending on competitors' efficiency, production capacity and aggregate demand, in addition to internal OPEC cohesion. Some authors have also examined how the market structure has evolved over time. Huppmann and Holz [2012], for example, argue that it moved from an oligopoly to a more competitive environment after the Great Recession.

With regard to empirical literature, as pointed out by Alvarez et al. [2020], macro-empirical literature has remained somewhat disconnected from theoretical studies on market strategies and has focused on understanding whether oil price fluctuations are dominated by unexpected variations in oil supply or changes in global demand. Early studies considered that the main driver of prices was supply, without reflecting more deeply on possible changes in drivers due to macroeconomic shocks. The focus shifted in the literature towards the late 2000s, when a growing consensus identified global demand conditions as the key factor explaining oil price movements, especially in specific episodes such as the 2008 crisis (see Kilian [2008], Kilian [2009], Kilian and Murpy [2014], Baumeister and Peersman [2013], Baumeister and Hamilton [2015]). Even in these studies, however, the analysis of the competitive structure of the global oil market plays a limited role in understanding structural shocks. Nevertheless, in some recent papers, OPEC is recognised as a

[1]The Western Texas Intermediate (WTI) crude oil price reached US $26.21 per barrel in February 2018, which until then is a record low since July 2002, while the US real import price fell with more than 73% in June 2014-February 2016.

[2]https://espresso.economist.com/06d172404821f7d01060cc9629171b2e

[3]https://espresso.economist.com/b8f36d2dffddf18ae2ff15d71c9eb62d

monopolist on the residual part of the demand curve (Caldara et al. [2019]), in others a relationship between market conditions and structural drivers of oil prices is identified (Kilian and Murpy [2014]). In recent years, the shale revolution has radically changed market conditions, raising the question on its influence on oil price dynamics (Foroni and Stracca [2019]) and its potential impact on Arab oil producers' economic policies (Kilian [2017]).

The game between OPEC and the shale oil producers has been analyzed before by Behar and Ritz [2017]. In determining the strategy of OPEC, they make a distinction between accommodation and squeeze strategies, where the latter is a strategy in which OPEC cuts the oil price by so much that the representative shale oil firm ceases production. They conclude that OPEC's squeeze strategy was the cause of the price drop in November 2014. In particular, Behar and Ritz [2017] suggest that an accommodation strategy is applied up to 2014, thereafter followed by a strategy where OPEC tried to defend its market share by flooding the market in an attempt to drive out shale producers. The latter explains the 2014-2016 drop in crude oil prices mentioned above (see also Brown and Huntington [2017], Coy [2015], Gause [2015], Manescu and Nuno [2015])[4].

Recently Alvarez et al. [2020] have tried to bridge the gap between theory and empirics with a SVAR model (following Kilian and Murpy [2014]), drawing a link between the structure of the market and the implications for structural empirical models of the global oil market. The authors show how strategic interactions between a dominant player and competitive fringe firms can affect the balance of the oil market. In particular, the leader (OPEC) can adopt alternative strategies, while the followers can take into consideration the market conditions and produce what their capacity allows. In particular, OPEC can act as a monopolist on the residual demand curve, and shift its production in tandem with the production of marginal firms. In their paper, Alvarez et al. [2020] identify two types of shock: the Market Share Targeting shock and the Price targeting shock, depending on which is the strategy adopted by the producers.

Our paper is an extension to Behar and Ritz [2017] in that our analysis is dynamic and we model the oil price to be uncertain. We consider an incumbent-entrant framework with the OPEC as incumbent and a representative shale-oil firm as the entrant. Over time the incumbent can choose any production volume it wants, whereas the entrant's quantity is fixed. However, the entrant has some flexibility in the sense that when the equilibrium oil price becomes too low, it can (temporarily) stop production so that it enters the mothballing state. When being in the mothballing state the entrant always has the option to start production again, which it will do once the oil price has risen to a sufficiently high level. Furthermore, we take account of the fact that the shale-oil producer has higher production costs. A thorough empirical investigation lies at the basis of the estimation of our model parameter values.

The fact that the mothballing option gives the entrant some flexibility, is especially beneficial if there is a lot of uncertainty about the oil prices. On the other hand, also the incumbent knows that when the oil price becomes too low, the entrant exercises its mothballing option and stops production. This gives room for OPEC to apply its squeeze strategy, i.e. by overproducing the oil price decreases, making it optimal for the entrant to enter the mothballing state. Would the shale-oil producer not have this possibility, and instead would be committed to a fixed production level, this would trigger OPEC to refrain from applying the squeeze strategy by overproducing. As a result this would enhance the entrant's payoff. We conclude that the mothballing option on the one hand benefits the entrant because it provides some flexibility in an uncertain market environment, but on the other hand it deprives the entrant from its commitment value. We find that flexibility dominates commitment if the market uncertainty is high, giving the mothballing option a positive value. However, in the complementary case of limited uncertainty it would be better for the entrant to be committed to its fixed production level, which induces the mothballing option to have a negative value.

We further find that the incumbent is especially inclined to apply the squeeze strategy in case of a high fixed production volume of the entrant. Then pushing the shale-oil firm in mothballing state would reduce market quantity considerably, pushing the price of oil up. An important take-away from our empirical

[4]The literature contains also other explanations for the fact that OPEC did not react by reducing production to maintain high prices in the years 2014-2016. One is that the shale oil revolution nullified OPEC's market power (shale oil has taken OPEC's role as swing producer), leaving its members no choice but to accept low prices (Baffes et al. [2015], Baumeister and Kilian [2016a], Baumeister and Kilian [2016b], Dale [2016] and Kaletsky [2015]). Yet another explanation is that OPEC was uncertain about the potential of shale oil and needed to test its resilience under low prices (Fattouh et al. [2016], Huppman and Livingston [2016]).

analysis is that the form of the demand function matters: a high demand elasticity results in a more frequent occurrence of the mothballing state.

In addition, a thorough empirical investigation lies at the basis of the estimation of our model parameter values. More in detail, by means of an application of the Generalized Method of Moments (GMM), we have been able to estimate the parameters of both the demand function and of the process introducing uncertainty in the model. For this purpose, together with time series of crude oil's price and world production, we exploited a set of instrumental variables correlated with the latter one.

The paper is organized as follows. After an overview of the literature in Section 2, the model is presented in Section 3. Our incumbent-entrant game is solved in Section 4 after which a thorough empirical analysis follows in Section 5. Section 6 concludes.

2 The Model

We consider two firms, representing OPEC and a firm representing the total shale-oil production of the US market. Firm 1 (OPEC in the example) is the market incumbent and the more efficient producer. Firm 1 is flexible in the sense that it is able to produce any production amount $q_1(t)$ it wants. Firm 1's production costs are without loss of generality set to zero.

Firm 2 is the market entrant and the less efficient (representative shale-oil producer in the example). Whenever it is in the production stage, it incurs a positive cost C. To be able to produce, Firm 2 must first enter the market paying a sunk cost equal to I_2. Firm 2 is a dedicated (non-flexible) producer in the sense that it either can produce a fixed quantity equal to $\bar{q}_2$ or zero. The firm is able to mothball its production temporarily, by leaving drilled wells uncompleted[5]. When it is in such a mothballing state it does not produce and has to pay maintenance costs equal to $M < C$. Firm 2 can go from the production to the mothballing state without incurring additional costs. Restarting production, i.e. going from the mothballing back to the production state is assumed to incur no additional costs either. The assumption of negligible suspension and resumption costs is supported by an analysis we performed on the cost breakdown of an investment in an representative shale oil rig. Based on government and industry reports (EIA [2016] and Crénes et al. [2017]) we set up a fictional representative shale oil rig, assuming average values for the size, the need for workforce and the lifespan. All expenses borne during the entire life of the project were then classified into sunk, production, maintenance, mothballing and resumption costs. The two last expense items are only related with the cost of hiring and firing the workforce. Quantified on the basis of SHRM [2016] their weight compared to the overall costs of the investment are approximately 0.09% and 0.19%, respectively, and can, therefore, be considered negligible.[6] The inverse demand function is given by

$$p = X(\alpha - \eta Q), \tag{1}$$

where X is a demand shock parameter assumed to follow a geometric Brownian motion equal to

$$dX = \mu X dt + \sigma X dz, \text{ with } X(0) > 0. \tag{2}$$

Here μ represents the constant drift, σ volatility and dz is the increment of a Wiener process. Q represents the total market output, which is either equal to

$$Q = q_1(t),$$

if only Firm 1 produces actively, or

$$Q = q_1(t) + \bar{q}_2,$$

if both firms produce actively. Both firms observe the realizations of the demand shock parameter X over time.

We assume that the two firms are playing a Stackelberg production game with Firm 1 as the Stackelberg leader, starting at the moment that the follower enters the market. We motivate this by the fact that OPEC

[5] Shale-oil producers can flexibly pause production if, for example, the price of oil drops. They can do so by leaving drilled wells uncompleted. If oil prices increase again then can complete (frack) those wells.

[6] All details of this analysis are available upon request.

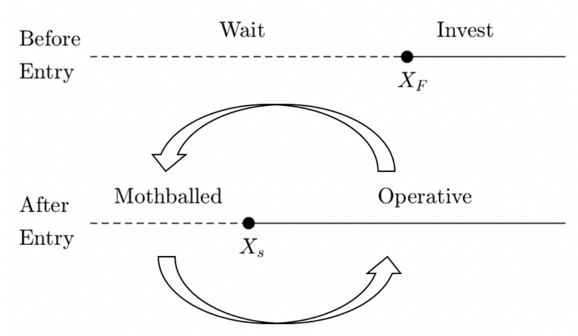

Figure 1: Illustration decision problem of Firm 2.

was playing its strategy against shale producers that are already in the market. Therefore, in setting the output, Firm 1, as the Stackelberg leader, announces its output first given the current realization of the demand shock parameter X. Then Firm 2 reacts. It either chooses to be active. i.e. $q_2 = \bar{q}_2$, or q_1 is so large, and thus price p is so low, that Firm 2 refrains from production so that $q_2 = 0$[7]. Note that we consider a dynamic framework and therefore, the firms revisit this production game at each moment in time t.

Figure 1 illustrates the decision problem of Firm 2. Upon investment, which occurs when demand reaches a level indicated by X_F, Firm 2 plays an output game with the incumbent Firm 1. X_s in Figure 1 indicates the level of the demand shock parameter X, at which it is optimal for Firm 2 to change the operation strategy. If X falls below X_s, Firm 2 mothballs production. It resumes production again as soon as X reaches the level X_s. In the following section, we will solve for the optimal levels of these thresholds (see Section 3.1 for the derivation of X_s, and Section 3.2 for the derivation of X_F). In what follows we first focus on the production output game, deriving the optimal strategy of the leader using the fact that it is able to produce flexible as opposed to the Stackelberg follower.

3 Model derivations

In this section we first analyze the optimal output game (Subsection 3.1) before continuing to derive the optimal investment strategy of the market entrant and the value functions of the two firms (Subsections 3.2 and 3.3).

3.1 Output game

We formulate the dynamic output game similar to Behar and Ritz [2017] along the lines that the leader can choose between two strategies referred to as *accommodate* and *squeeze* strategy, respectively. When applying the *squeeze* strategy, the leader chooses its output quantity in order to force the follower into suspension. If squeezing the follower out of the market is too expensive for the leader, i.e. leads to suboptimal profit, it will accommodate the follower in the market. For changing levels of X over time the leader will choose the optimal strategy.

We solve the output game in a backward fashion starting with solving for the optimal output decision of the follower given the leader is producing with a quantity q_1. Note that we assumed that mothballing and resumption of operation is costless for the follower. This means that the decisions to temporarily suspend production (i.e. mothball) and resume production are completely reversible and therefore, NPV decisions. The follower will produce as long as the profit from producing is larger than the maintenance costs. The instantaneous profit of the follower in the production state is equal to $X(\alpha - \eta(q_1 + \bar{q}_2))\bar{q}_2 - C\bar{q}_2$, while it pays costs equal to $-M\bar{q}_2$ per time period in the suspension state. Therefore, the profit of the follower for

[7]This is what happened, for example, in Vienna on November 30.

a given quantity q_1 produced by the Stackelberg leader is equal to

$$\pi_F(X, q_1) = \begin{cases} X(\alpha - \eta(q_1 + \bar{q}_2))\bar{q}_2 - C\bar{q}_2 & \text{if } q_1 < \frac{1}{\eta}\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right) \text{ or } X > \frac{C-M}{\alpha - \eta(q_1 + \bar{q}_2)}, \\ -M\bar{q}_2 & \text{otherwise.} \end{cases} \tag{3}$$

For a given demand level X the follower will suspend if the quantity of the leader q_1 is greater than $\frac{1}{\eta}\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right)$. This means that the leader can squeeze the follower out of the market by setting its output quantity to a level $q_1 \geq \frac{1}{\eta}\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right)$, where $q_{1,s} = \frac{1}{\eta}\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right)$ denotes the lowest level for a given X that allows the leader to squeeze the follower out of the market. For a given level of q_1 the follower suspends if the current value of X lies below $\frac{C-M}{\alpha - \eta(q_1 + \bar{q}_2)}$.

Now we consider the strategy of the leader in the output game. The profit of the leader is equal to

$$\pi_L(X) = \begin{cases} X(\alpha - \eta q_1)q_1 & \text{if the follower is in suspension,} \\ X(\alpha - \eta(q_1 + \bar{q}_2))q_1 & \text{if the follower is producing.} \end{cases} \tag{4}$$

Given the follower is in the suspension state we can distinguish two cases. Note that the leader earns the optimal monopoly profit for a production amount equal to $q_{1,mon} = \frac{\alpha}{2\eta}$ and that there is an upper boundary $\bar{q}_1 = \frac{\alpha}{\eta}$ for the leader to earn a positive monopoly profit. The leader can keep the follower in the suspension state producing its optimal "monopoly-quantity" $q_{1,mon}$ as long as $q_{1,mon} \geq q_{1,s}$ or $X \leq \frac{2(C-M)}{\alpha - 2\eta\bar{q}_2}$. We define this boundary on the demand shock parameter by

$$X_{s,mon} = \frac{2(C-M)}{\alpha - 2\eta\bar{q}_2}. \tag{5}$$

The optimal output quantity in order to apply the squeeze strategy is, therefore, equal to $max[q_{1,s}, q_{1,mon}]$. If $X \leq X_{s,mon}$, i.e. demand is relatively low, the leader can keep the follower out of the market "for free" by simply producing the optimal monopoly quantity $q_{1,mon}$. Otherwise, the leader needs to overproduce with an amount equal to $q_{1,s}$ in order to squeeze the follower out of the market. The leader accommodates the follower by producing the quantity $q_{1,a} = \frac{\alpha - \eta\bar{q}_2}{2\eta}$.

We denote the profit of the leader using the accommodation strategy by $\pi_{L,a}(X)$, which is equal to $X\frac{\left[\alpha^2 - \eta^2\bar{q}_2^2\right]}{4\eta}$. The profit of the leader using the squeeze strategy is equal to

$$\pi_{L,s}(X) = \begin{cases} X\frac{\alpha^2}{4\eta} & X \leq X_{s,mon}, \\ X\frac{1}{\eta}\left(\eta\bar{q}_2 + \frac{C-M}{X}\right)\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right) & X > X_{s,mon}. \end{cases} \tag{6}$$

It is optimal for the leader to play the squeeze strategy if X is such that $\pi_{L,s}(X) > \pi_{L,a}(X)$. It is straightforward to show that this holds if $X < X_s$, with

$$X_s = \frac{2(C-M)}{\alpha - 3\eta\bar{q}_2}. \tag{7}$$

Note that a suspension region only exits if the condition $\bar{q}_2 < \frac{\alpha}{3\eta}$ holds. This means that the follower cannot be "too big".

Figure 2 illustrates the optimal output quantity and resulting profit of the Stackelberg leader as functions of the demand shock parameter X.

We summarize the optimal production quantities and profit of the leader and follower for the different strategies in the following proposition.

Proposition 1 *The optimal production quantity and profit of the leader for a given X and $\bar{q}_2$ are equal to*

$$q_1^*(X) = \begin{cases} \frac{\alpha}{2\eta} & X \leq X_{s,mon}, \\ \frac{1}{\eta}\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right) & X_{s,mon} < X \leq X_s \\ \frac{\alpha - \eta\bar{q}_2}{2\eta} & X > X_s. \end{cases} \tag{8}$$

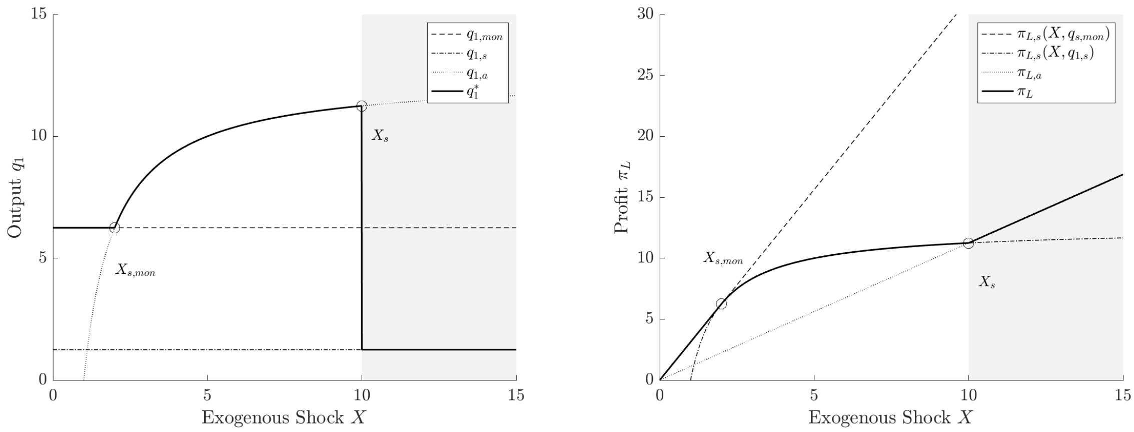

Figure 2: Optimal output decision (left panel) and resulting profit (right panel) of Firm 1 as a function of the exogenous shock X.

$$\pi_L(X) = \begin{cases} X\frac{\alpha^2}{4\eta} & X \leq X_{s,mon} \\ X\frac{1}{\eta}\left(\eta\bar{q}_2 + \frac{C-M}{X}\right)\left(\alpha - \eta\bar{q}_2 - \frac{C-M}{X}\right) & X_{s,mon} < X \leq X_s \\ X\frac{\left[\alpha^2-\eta^2\bar{q}_2^2\right]}{4\eta} & X > X_s \end{cases} \tag{9}$$

where

$$X_s = \frac{2(C-M)}{\alpha - 3\eta\bar{q}_2}, \tag{10}$$

and

$$X_{s,mon} = \frac{2(C-M)}{\alpha - 2\eta\bar{q}_2}. \tag{11}$$

The profit flow of the follower is then equal to

$$\pi_F(X) = \begin{cases} \frac{X}{2}(\alpha - \eta\bar{q}_2)\bar{q}_2 - C\bar{q}_2 & X > X_s \\ -M\bar{q}_2 & X \leq X_s \end{cases} \tag{12}$$

3.2 Optimal investment decision and value function of the market entrant

In the following we derive the optimal investment decision and resulting value function of the market entrant Firm 2. Given that Firm 1 is the market incumbent, the follower's investment decision involves no strategic aspects. The market entrant has to determine the optimal investment timing, which is similar to fixing a threshold level X_F.

The market entrant's investment decision is solved as an optimal stopping problem which can be formalised as

$$V_F(X_0) = \sup_{\tau \geq 0} E\left[\int_{t=\tau}^{\infty} \pi_F(X(t))e^{-rt} - I_2 e^{-r\tau} \mid X(0) = X_0\right]. \tag{13}$$

To properly define the optimal stopping problem we need to define different states. We denote the idle, operating and mothballing states of the market entrant by the labels i, o and s, respectively. We find the value of the firm in each state as the appropriate combinations of the expected profit or cost streams and the options to switch.

After investment the firm must decide whether and when to mothball operation. Given the results presented in Section 3.1 Firm 2 will suspend the operating project if the price falls to a threshold X_s. Given the project is in the mothballing state, the firm will reactivate it if the price rises above this threshold again.

The firm is in an idle state over the interval $(0, X_F)$. Standard real options analysis (see, e.g., Dixit and Pindyck [1994]) shows that the value in the idle state, i.e. the value of the option to invest, is equal to

$$V_i(X) = AX^{\beta_1}, \tag{14}$$

where A is a positive constant that remains to be determined and β is the positive root of the quadratic polynomial

$$\frac{1}{2}\sigma^2\beta^2 + \left(\mu - \frac{1}{2}\sigma^2\right)\beta - r = 0, \tag{15}$$

so that

$$\beta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\mu}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}. \tag{16}$$

Upon investment the operating state prevails over the interval (X_s, ∞), where the value of the firm is given by the following equation:

$$V_o(X) = BX^{\beta_2} + \frac{X}{2(r-\mu)}(\alpha - \eta\bar{q}_2)\bar{q}_2 - \frac{C\bar{q}_2}{r}, \tag{17}$$

where β_2 is the negative root of equation 15 given by

$$\beta_2 = \frac{1}{2} - \frac{\mu}{\sigma^2} - \sqrt{\left(\frac{1}{2} - \frac{\mu}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}, \tag{18}$$

and B a constant that remains to be determined. The suspension state continues over the range of $(0, X_s)$. The value of the suspended project is given by

$$V_s(X) = DX^{\beta_1} - \frac{M\bar{q}_2}{r}, \tag{19}$$

where constant D remains to be determined. At the switching points X_F and X_s, we have to apply appropriate value matching and smooth-pasting conditions. For the original investment, the conditions are equal to

$$\begin{aligned} V_i(X_F) &= V_o(X_F) - I_2, & (20)\\ V_i'(X_F) &= V_o'(X_F). & (21) \end{aligned}$$

For suspension and resumption, the conditions are

$$\begin{aligned} V_o(X_s) &= V_s(X_s), & (22)\\ V_o'(X_s) &= V_s'(X_s). & (23) \end{aligned}$$

This system of four equations determines the threshold X_F and the three constants A, B and D.

The solution of the optimal investment threshold and value function for the market entrant is summarized in the following proposition.

Proposition 2 *The optimal value function of the market entrant is given by*

$$V_i(X) = AX^{\beta_1}, \tag{24}$$

before investment, and

$$V_F(X) = \begin{cases} BX^{\beta_2} + \frac{X}{2(r-\mu)}(\alpha - \eta\bar{q}_2)\bar{q}_2 - \frac{C\bar{q}_2}{r}, & \text{for } X > X_s \\ DX^{\beta_1} - \frac{M\bar{q}_2}{r}, & \text{for } X \leq X_s \end{cases} \tag{25}$$

upon investment, with

$$A = \frac{\beta_2}{\beta_1} B X_F^{\beta_2-\beta_1} + \frac{X_F^{1-\beta_1}}{\beta_1} \frac{(\alpha-\eta\bar{q}_2)\bar{q}_2}{2(r-\mu)}, \quad (26)$$

$$B = X_s^{-\beta_2} \left(\frac{1}{\beta_1-\beta_2}\right) \left[(1-\beta_1)\frac{X_s(\alpha-\eta\bar{q}_2)\bar{q}_2}{2(r-\mu)} + \beta_1 \frac{(C-M)\bar{q}_2}{r}\right], \quad (27)$$

$$D = X_s^{-\beta_1} \left(\frac{1}{\beta_1-\beta_2}\right) \left[(1-\beta_2)\frac{X_s(\alpha-\eta\bar{q}_2)\bar{q}_2}{2(r-\mu)} + \beta_2 \frac{(C-M)\bar{q}_2}{r}\right]. \quad (28)$$

The optimal investment threshold X_F is given implicitly by the solution of the following equation

$$(\beta_1-\beta_2)BX_F^{\beta_2} + (\beta_1-1)\frac{X_F(\alpha-\eta\bar{q}_2)\bar{q}_2}{2(r-\mu)} - \beta_1\frac{C\bar{q}_2}{r} - \beta_1 I_2 = 0. \quad (29)$$

Analysing the options to mothball and to resume operation, we find that the option to mothball production can have negative value. The following corollary states the condition under which this is the case.

Corollary 3 *The option to mothball production, BX^{β_2}, has a negative value if the following condition holds:*

$$2\beta_1\eta\bar{q}_2(r-\mu) + (\beta_1\mu - r)(\alpha-\eta\bar{q}_2) > 0. \quad (30)$$

The condition presented in Corollary 3 holds if β_1 is relatively large. Therefore, we can conclude that in relatively certain economic environments, i.e. σ is small[8], the value of the option to mothball production is negative.

A firm would like to mothball if demand is low. In this case its quantity can only be sold at a low price, which could result in a negative profit margin. So on the one hand the mothballing option makes the entrant more flexible in that it can stop production in such a situation. On the other hand, in a strategic setting mothballing has a disadvantage in that the entrant has no commitment value. The point is that the incumbent knows that the entrant will temporarily leave the market at the moment that demand falls. The incumbent is able to force this situation by increasing its quantity, which is bad for the entrant's profit. However, in a situation that the mothballing option is not present, the entrant would be committed to produce the amount $\bar{q}_2$. The incumbent knows this and therefore would not overproduce, which would be good for the entrant. Hence, to evaluate the value of the option to mothball one has to consider flexibility versus commitment. The value of flexibility, and thus the value of the mothballing option, is particularly high when there is a lot of demand uncertainty, because then it is more likely that low values of X will occur and the firm would like to mothball. It follows that in the complementary case of a modest demand uncertainty level the commitment value will dominate the low value of flexibility, resulting in a negative value of the mothballing option.

3.3 Value function of the incumbent

In the next step we determine the value function of the incumbent. Therefore, we first consider the leader's profit function for a given level of X when both firms are active in the market as given by equation 9.

The leader's value function $V_L(X)$ and profit function $\pi_L(X)$ given that Firm 2 has entered the market has to satisfy the following differential equation

$$\frac{1}{2}\sigma^2 X^2 \frac{\partial^2 V_L}{\partial X^2} + \mu X \frac{\partial V_L}{\partial X} - rV_L + \pi_L = 0. \quad (31)$$

Substituting $\pi_L(X)$ into this equation and applying value matching and smooth pasting at $X = X_{s,mon}$ and $X = X_s$ leads to the following value function for the leader

[8] This follows from the fact that $\frac{\partial\beta_1}{\partial\sigma} < 0$ which can be easily shown.

$$V_L(X) = \begin{cases} LX^{\beta_1} + \frac{X}{r-\mu}\frac{\alpha^2}{4\eta} & X \leq X_{s,mon} \\ M_1 X^{\beta_1} + M_2 X^{\beta_2} + \frac{X\bar{q}_2(\alpha - \eta\bar{q}_2)}{r-\mu} + \frac{(C-M)}{r\eta}(\alpha - 2\eta\bar{q}_2) - \frac{(C-M)^2}{\eta X(r+\mu-\sigma^2)} & X_{s,mon} < X \leq X_s \\ NX^{\beta_2} + \frac{X}{r-\mu}\frac{\left[\alpha^2 - \eta^2\bar{q}_2^2\right]}{4\eta} & X > X_s \end{cases}$$

where

$$\begin{aligned} L &= X_{s,mon}^{-\beta_1}\left(\frac{1}{\beta_1 - \beta_2}\right)\left[\frac{X_{s,mon}}{r-\mu}\frac{\alpha^2}{4\eta}(\beta_2 - 1) - \mathcal{M}_1 X_{s,mon}^{\beta_1}(\beta_2 - \beta_1) - \frac{(C-M)\alpha}{r\eta}\beta_2\right. \\ &\quad + \frac{(C-M)^2}{\eta X_{s,mon}(r+\mu-\sigma^2)}(\beta_2 + 1) \end{aligned}$$

(33)

$$M_1 = X_s^{-\beta_1}\left(\frac{-1}{\beta_1 - \beta_2}\right)\left[\frac{X_s}{r-\mu}\frac{\left[\alpha^2 - \eta^2\bar{q}_2^2\right]}{4\eta}(\beta_2 - 1) - \frac{(C-M)\alpha}{r\eta}\beta_2 + \frac{(C-M)^2}{\eta\bar{X}_s(r+\mu-\sigma^2)}(\beta_2 + 1)\right] \quad (34)$$

$$M_2 = X_{s,mon}^{-\beta_2}\left(\frac{1}{\beta_1 - \beta_2}\right)\left[\frac{X_{s,mon}}{r-\mu}\frac{\alpha^2}{4\eta}(\beta_1 - 1) - \frac{(C-M)\alpha}{r\eta}\beta_1 + \frac{(C-M)^2}{\eta X_{s,mon}(r+\mu-\sigma^2)}(\beta_1 + 1)\right] \quad (35)$$

$$\begin{aligned} N &= X_s^{-\beta_2}\left(\frac{1}{\beta_1 - \beta_2}\right)\left[M_2 X_s^{-\beta_2}(\beta_1 - \beta_2) - \frac{X_s}{r-\mu}\frac{\left[\alpha^2 - \eta^2\bar{q}_2^2\right]}{4\eta}(\beta_1 - 1) + \frac{(C-M)\alpha}{r\eta}\beta_1\right. \\ &\quad - \frac{(C-M)^2}{\eta X_s(r+\mu-\sigma^2)}(\beta_1 + 1) \end{aligned}$$

(37)

The value function in equation (32) is split into three regions. In the demand region $X \leq X_s$ it is optimal for Firm 1 to squeeze Firm 2 out of the market. This leaves the incumbent as the only active producer in the market earning a high profit. This squeeze region is split into two areas. For very low demand, i.e. X such that $X \leq X_{s,mon}$, Firm 1 can keep Firm 2 in the mothballing state by simply producing the optimal monopoly output. Here the value function consists of two terms, where the second term represents the expected total discounted revenue the incumbent obtains when it is in the market earning optimal monopoly profits forever. The first term of the value function represents a negative factor that corrects for the fact that demand might eventually increase so that Firm 1 has to change its strategy to overproduce in order to keep Firm 2 in the mothballing state. In this region the value function of Firm 1 consists of five terms, where the three last ones represent the total expected discounted revenue of the incumbent in case it would apply this strategy forever. The first term is negative representing a correction term for the fact that demand might rise such that it becomes too expensive for Firm 1 to squeeze Firm 2 out of the market and therefore, it will have to accommodate its competitor. The second term represents the option that demand might decline in which case the incumbent can earn monopoly profits. For demand levels such that $X > X_s$, the demand is so high that it is optimal for Firm 2 to be active and produce. The second term in the leader's value function in this region represents the expected total discounted revenue it obtains when both firms would be active forever. The first term represents the value of the option that the demand might fall below the mothballing threshold of Firm 2, which would leave Firm 1 as the only producer in the market.

Before Firm 2's market entry, the incumbent's value function is equal to

$$V_{L,m}(X) = \mathcal{O}X^{\beta_1} + \frac{X}{r-\mu}\frac{\alpha^2}{4\eta}, \quad (38)$$

where the constant $\mathcal{O}$ remains to be determined. This constant can be determined by acknowledging that the incumbent's value function right after Firm 2's entry is equal to

$$V_{L,a}(X) = NX^{\beta_2} + \frac{X}{r-\mu}\frac{1}{4\eta}\left[\alpha^2 - \eta^2\bar{q}_2^2\right], \tag{39}$$

and applying the value matching condition $V_{L,m}(X_F) = V_{L,a}(X_F)$ at the market entrant's investment threshold, X_F, leading to

$$\mathcal{O} = X_F^{-\beta_1}\left[NX_F^{\beta_2} - \frac{X_F}{r-\mu}\frac{\eta\bar{q}_2^2}{4}\right]. \tag{40}$$

Intuitively, $\mathcal{O}$ is negative as $\mathcal{O}X^{\beta_1}$ corrects for the fact that when $X(t)$ reaches X_F, Firm 2 enters the market which ends the incumbent's monopolistic privilege. Note that the market entrant would never invest just to enter into a mothballing state.

4 Application

4.1 Empirical Estimation

The theoretical model described in the previous sections is based on a specific demand function for crude oil, defined in equation (1). We now present the estimation of the parameters of the demand function. In this framework, crude oil market price is linear in quantity, but the intercept and the slope of this relation are assumed to be affected by an exogenous shock. This disturbance is drawn by the unobserved GBM defined in equation (2). As crude oil market price is a key variable in defining the dynamics of the output game between market leader and follower, the estimation of the four parameters of equations (1) and (2) is crucial to provide an empirical validation to the model. In addition, these estimates allow to compute those triggers at which a change-in-state occurs, that is those prices in correspondence of which the market leader changes its strategy implementing a squeeze-out or accommodation strategy.

The solution to equation (2) is:

$$X(t) = X(0)\exp\left\{\left(\mu - \frac{\sigma^2}{2}\right)t + \sigma W(t)\right\}, \tag{41}$$

where $X(0) > 0$ is the positive starting point of the GBM. By plugging this expression into equation (1) and after rearrangements, it follows that:

$$\sigma W(t) = \ln p(t) - \ln X(0) - \left(\mu - \frac{\sigma^2}{2}\right)t - \ln(\alpha - \eta Q(t)) \sim \mathcal{N}\left(0, \sigma^2 t\right), \tag{42}$$

where $W(t)$ is the increment of a Wiener process. We are interested in calibrating the parameters of the GBM, μ and σ, and of the inverse demand function, α and η.

The value of η is intrinsically related to the price elasticity of the demand of oil, a parameter which has been extensively investigated, and for which a wide range of possible values have been proposed. Caldara et al. [2019] review the results provided by the empirical literature, and provide their own four estimates of the demand price elasticity from alternative structural VAR specification and identification assumptions. In our framework, their results are consistent with four values of η ranging from about 2.8 to about 58.8. Conditional on each of these alternative values of η, we resort to the GMM estimation principle to estimate the remaining parameters.

More specifically, we exploit the following set of orthogonality conditions:

$$\mathbb{E}\left[\sigma W(t) Z_i(t)\right] = 0 \tag{43}$$

and:

$$\mathbb{E}\left[\sigma^2 W^2(t) - \sigma^2 t\right] = 0, \tag{44}$$

where $Z_i(t)$, $i = 1, ..., k$ are (instrumental) variables uncorrelated with the increment of the Wiener process. The use of instrumental variables is dictated by the need to solve a classic identification problem: prices and

Parameter	Estimate			
	Case I	**Case II**	**Case III**	**Case IV**
α	490.7808***	268.4805***	104.0361***	23.1193***
	(2.1957)	(1.2041)	(0.4666)	(0.1037)
η	58.8235	32.2581	12.5000	2.7778
μ	.0086***	.0086***	.0087***	.0104***
	(.0010)	(.0010)	(.0010)	(.0025)
σ	.0111***	.0145***	.0205***	.0613***
	(.0008)	(.0010)	(.0007)	(.0277)

Table 1: Results of the estimation of equation (42). The standard error is reported in brackets, while *** denotes statistical significance at the 1% level.

quantities are jointly determined by the interplay of supply and demand, which creates an endogeneity issue to be solved in order to obtain consistent estimates of the parameters of interest (see e.g. Ullah et al. [2018]). In our framework, order to identify and estimate the parameters of the oil demand function, the instrumental variables should be correlated to the oil supply but not correlated to demand shocks. The literature (e.g. Lin [2011]) suggests a wide range of possible supply shifters (e.g. estimated reserves, rig count). In our study we have tested several variables to this role and we have chosen those with the highest correlation with the variable $Q(t)$ to be instrumented (both in terms of pairwise correlations and in multiple linear regression model). As a result, we identified the following four variables: world count of active rigs, estimated world crude oil reserves,[9] the growth of GDP of Middle East and North Africa and the STOXX Europe 600 Oil & Gas index. A full discussion of the time series $Q(t)$ and $Z_i(t)$ used in the paper is provided in the appendix.

The 1-step GMM estimates of μ, σ and α based on monthly data from April 2004 to June 2018,[10] for the four values of η considered are presented in Table 1. Going from the least elastic ($\eta = 58.8$) to the most elastic scenario ($\eta = 2.8$) the estimate of the intercept of the demand function, $\hat{\alpha}$, decreases at the same pace, from 490.8 to 23.1. For what concerns the estimated values of the GBM parameters, $\hat{\mu}$ is around 0.009 in most scenarios, whereas $\hat{\sigma}$ rises from 0.01 to 0.06 from the least to the most elastic case. This result may be interpreted as a proof that the inverse demand function is a relation which is relatively stable over the long-run, because of the low value of the drift parameter μ. In addition, the presence of a non-negligible diffusion parameter σ allows the presence of short-term volatility.

4.2 Case study

Given the results from Section 4.1 we now proceed to parametrize the model with respect to the parameters representing the market follower in order to derive the results for the theoretical model presented in Section 2. For our case study we assume that the market follower is represented by a fictional firm representing the whole US shale market. Specifically, we need to estimate the variable production and suspension costs – to be borne during operating and mothballing stages, denoted as C and M, respectively – together with a valuation of the market follower's investment sunk cost and production – denoted as I_2 and $\overline{q}_2$, respectively.

For this purpose we have considered an average fictional shale oil rig, representative of the whole industry, to study its cost breakdown and production. Then, given the median number of active shale oil rigs in the considered period[11], we have generalized these results to represent the features of the market follower.

In more detail, thanks to the breakdown provided by Crénes et al. [2017], we have been able to split out the overall expenditure of the average shale rig between sunk and production costs.[12] Moreover, considering the estimated maintenance costs provided by the same authors, we have also been able to compute the cost of

[9]We refer to proven oil reserves, that is, those for which there is a probability greater than 90% that the oil will be recovered.

[10]With the only exception of GDP data, which are only available on a quarterly basis.

[11]In according to the report provided by Baker Hughes (see: https://bakerhughesrigcount.gcs-web.com), over the period between April 2004 and Hune 2018 the median number of active shale rigs is 2650.

[12]The average cost of building a shale oil rig and operating it for its entire lifespan is about USD 22 million (https://www.investopedia.com/ask/answers/061115/how-do-average-costs-compare-different-types-oil-drilling-rigs.asp). Before an eventual re-fraking, the production stages last for about one year in average.

a period of suspension, which in this study has been arbitrarily set equal to six months. In conclusion, taking into account this suspension period, the overall cost of the average shale oil rig rises to USD 23.44 million, divided between sunk, operating and maintenance cost for the 61.61%, 31.35% and 6.3% respectively. Given the median number of shale oil rigs and considering an average production of $1,000$ bbl/day, in accordance to EIA [2020], the values for parameters I_2 and $\bar{q}_2$ follow. Production and maintenance costs are finally expressed in terms of USD per barrel produced.[13] The results of this analysis are summarized in Table 2.

Parameter	Value	Unit	Description
I_2	20.544	USD$\times 10^9$	Follower's sunk cost
$\bar{q}_2$	.954	bbl$\times 10^9$	Follower's output
C	20.411	USD/bbl	Production cost
M	3.911	USD/bbl	Maintenance cost
r	.03	–	Discount rate

Table 2: Parameter values for the base case.

The interest rate used in this case study is set equal to 3%, which is in line with the literature.[14] We have however performed a sensitivity analysis on the interest rate and find that results shown in the following are basically not sensitive to variations in r.[15]

Parameter	**Estimate**			
	Case I	**Case II**	**Case III**	**Case IV**
$X_{s,mon}$	0.0872	0.1595	0.4115	1.8519
X_s	0.1023	0.1873	0.4834	2.1755
X_F	0.1182	0.2163	0.5582	2.5121
$q_{1,a}$	3.6946	3.6844	3.6844	3.6844
$q_{1,m}$	4.1716	4.1614	4.1614	4.1614
$p(X_s)$	22.2436	22.265	22.265	22.265
$p(X_{s,mon})$	21.3921	21.4076	21.4076	21.4077

Table 3: Numerical results for the base case parameter set.

Table 3 presents the results using our base case parameter set presented above considering the four different levels of η. For all four cases the price at the resulting optimal mothballing threshold X_s from our analysis is approximately equal to 22. This price level represents the threshold below which the market follower suspends the production, since the revenue from producing is lower than the production costs. For this reason, X_s does not have to be intended as the break-even price – under which new wells are not constructed, but those existing ones remain in function. But it can be interpreted as a shut-in price, under which the production ceases. With regard to the period considered here, studies have reported that the break-even price was between 40 and 50 USD per barrel, while the shut-in price (lower than the previous one by definition) ranged between 23 and 30 USD per barrel (see Federal Reserve Bank of Dallas [2020] for further details). Our findings are in line with the lower values of this range. As there is no clear consent about the production costs in the literature[16] we performed comparative statics assuming different values for the overall total cost all leading to a suspension threshold that translates into prices within the aforementioned range.[17] Figure 3 illustrates the optimal output quantity of the market incumbent as a function of the demand shock parameter X. It shows that the optimal accommodation quantity of the incumbent is equal to $3.69x10^9$ barrel. If the demand shock parameter falls below the suspension threshold X_s the incumbent will increase its quantity to a value in the range of $(4.16, 4.64)$ depending on the realization of X in order to

[13]In this exercise we have also evaluated the possible cost of switching between production and suspension or *viceversa*. They are basically related to the cost of hiring and firing workforce and have been found to be negligible, because of the small dimension of shale oil rigs.

[14]For example Genc [2017] uses $r = 2\%$, while Lund and Nymoen [2018] prefer $r = 4\%$.

[15]The results of this analysis are available upon request.

[16]In the sources we considered the production cost ranges from a minimum of 16 million to a maximum of 28 million dollars .

[17]The detailed results of this analysis are available upon request.

squeeze the entrant out. If X falls below $X_{s,mon}$ the incumbent can keep the market entrant in mothballing "for free" by producing its optimal monopoly quantity equal to 4.16. Figure 4 shows the corresponding price resulting from the optimal strategy of the incumbent and market entrant as a function of the demand shock parameter X.

Note that for our base case parameter set the condition of Corollary 3 holds resulting in a negative mothballing option value for the market entrant as the volatility is relatively low ranging between 0.01 and 0.06 for our case study. For the parameter set of CASE IV, for example, keeping all remaining parameters constant, the volatility would have to increase above approximately 0.1

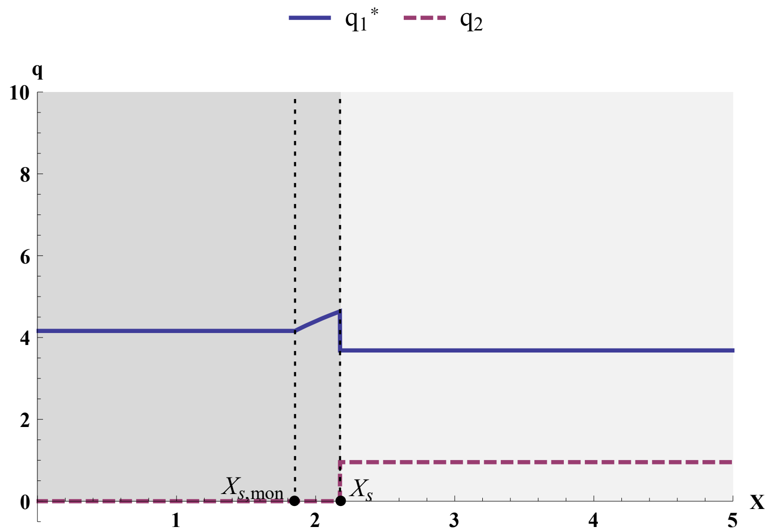

Figure 3: Optimal output quantities of the incumbent and market entrant as functions of X for the CASE IV parameter set.

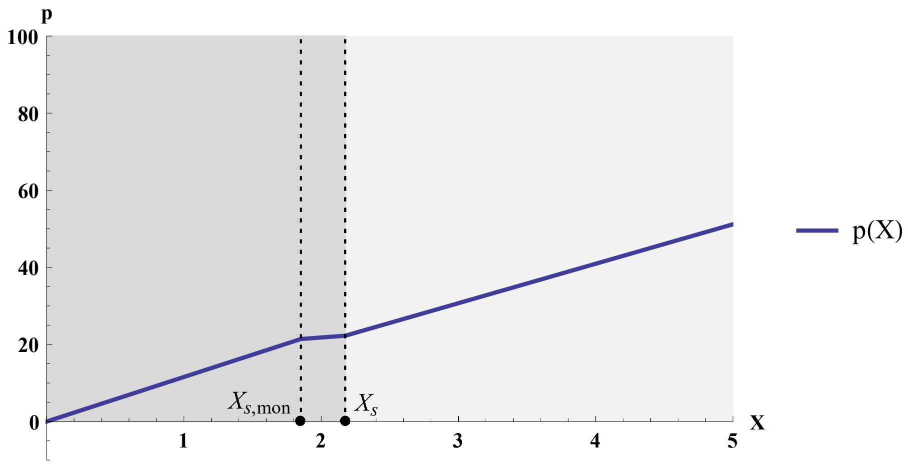

Figure 4: Price plotted as a function of X for the CASE IV parameters.

5 Conclusions

The incumbent-entrant game between OPEC and the representative oil producer learned that OPEC's squeeze strategy by which the shale-oil producer is pushed in the mothballing state, could result in a negative valuation of the entrant's mothballing option. We found that this especially happens in the case of a moderate market uncertainty. If there is a lot of uncertainty about oil prices, then the mothballing option value is definitely positive, induced by the additional flexibility it generates. In particular, being able to mothball gives the entrant the possibility to temporary leave the market, which is beneficial in case the oil price would be so low that it results in a negative profit margin. We further found that the incumbent should apply the squeeze strategy more often in case of a substantial market share of the entrant and a high demand elasticity.

Admittedly, the analysis of our mothballing game simplified a lot after we found out that in the shale oil industry there were hardly any sunk costs associated with entering or exiting the mothballing state. The implication is that in our game the decision to enter and leave the mothballing state is completely determined by the profit margin becoming negative and positive, respectively. Of course there are industries where mothballing transitions go along with incurring sunk costs. The resulting game will then be much more complex, but solving it is still a nice challenging future research topic.

A Descriptive statistics and instrumental variables

In Table 4, we provide descriptive statistics for the instrumental variables introduced in Section 4.1 to explain crude oil world production and on the latter one. The world count of active rigs, the estimated world crude oil reserves, the growth of GDP of Middle East and North Africa and the STOXX Europe 600 Oil & Gas Index are denoted as Z_i, with $i = 1, \dots, n$, while crude oil world production is denoted as Q. Notice that, for tractability purposes, all series have been expressed in the same order of magnitude.[18]

Table 5 provide the correlation matrix between crude oil world production and instrumental expected to have predictive power on that, together with levels of p-values for testing the hypothesis that there is no relationship between the observed phenomena. From these results, it is clear that the requirements of instrumental variables to be correlated with supply is always satisfied, with a statistical significance at least of 5%.

The predictive power that instrumental variables have on crude oil world production has been also verified by mean of the following IV regression:

$$q_t = \beta_0 + \underline{\beta}' \underline{Z_t}, \tag{45}$$

where supply is estimated using the set of instrumental variables as regressors.

Figure 5 shows the plots of the chosen IVs (left panel) and the result of the estimation of equation (45) together with the series of observed crude oil production (right panel). We notice that the estimated series of crude oil production well fits observed data. This conclusion is supported by results provided in table 6: the estimates of all coefficients of equation (45) are always significant with an interval of confidence equal to 1%, the adjusted R^2 is equal to .846 and the F-statistic against the constant model shows a p-value equal to 0, again with an interval of confidence of 1%.

In addition to the strongly positive intercept, representing the production not dependent on involved regressors, we notice the relevant positive impact on crude oil production of estimated world crude oil reserves. This relation, already pointed out by Lin [2011], is due to the fact that, as a consequence of the extension of recoverable reserves, additional wells are normally drilled to outline the productive limits of the reservoir, in according to Farzin [2001]. All other variables, even if significant, have a weaker effect on crude oil production. We notice the positive effect of the oil market index, which is explained by the fact that the healthier the oil companies, the greater the investments and thus the production, despite the long lead times for investment and technology development and deployment to provide benefits, remarked by Mullen and Lynn [2012]. Moreover, it is possible that, as in this case, the relation between active rigs and crude oil production is negative. The study of Apergis et al. [2016] highlight this feature with a focus on the six major oil producing regions in the U.S. Other authors explain this fact with a possible delay between a decline in rig count and a peak and decline in production.[19] Finally, the slightly negative yet significant impact of the GDP of Middle East and North Africa confirms the findings of some of the models of Lin [2011], which also finds that world GDP has always a surprising negative effect on production.

[18] More specifically, Z_1, Z_2 and Z_4 are expressed in terms of 10^3, 10^{18} barrels and 10^2 EUR respectively, while Q is expressed in terms of 10^7 barrels per day.

[19] Can we cite this? https://peakoil.com/business/the-divergence-of-rig-count-oil-price-and-production-explained

	Z_1	Z_2	Z_3	Z_4	Q
Mean	2.8300	1.5635	0.0048	3.3443	7.5922
Median	3.0090	1.6420	0.0201	3.2247	7.4380
Maximum	3.9000	1.7280	.1085	4.5599	8.2630
Minimum	1.4050	1.3630	−.2876	2.5402	7.1320
Std. Dev.	.6391	.1383	.0345	.4780	.3319
Skewness	−.4435	−.3368	−3.7245	.7025	.6309
Kurtosis	2.0166	1.3578	35.3849	2.6679	1.9436

Table 4: Descriptive statistics of crude oil world production and instrumental variables.

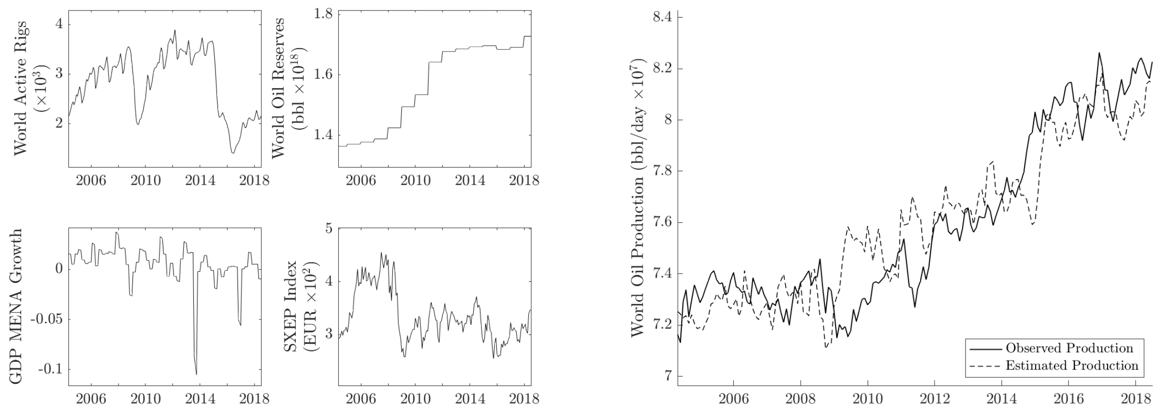

Figure 5: Instrumental variables used in the IV regression (left panel, from top left clockwise: world count of active rigs, estimated world oil reserves, STOXX Europe 600 Oil & Gas and GDP in Middle East and North Africa) to linearly estimate crude oil world production (right panel).

B Market Analysis

The core content of this paper is the chance of mothballing, available to shale industry operators, in case of not enough favorable market price. Then, in addition to the empirical estimation and to the case study provided in sections 4.1 and 4.2, it is useful to analyze market data in order to verify whether there is a contraction in shale oil sector in correspondence of crude oil drops. Because of the supposed sensitivity to crude oil downfalls, for this analysis we focused on the period between February 2014 and January 2016, that is around the biggest price variation observed since the beginning of shale revolution. Among the other variables, figure 6 shows the course of both crude oil price and shale oil rigs in the US, which is considered as a proxy of shale sector health.

On the basis of a graphical analysis we immediately notice the common behavior, which is confirmed by the correlation coefficient ρ between the two series equal to 0.72. More importantly, we also notice that the behavior of rigs count appears to be staggered with respect to those of price, in fact shale rigs count appears to react to price fluctuations with a lag of few months. This insight is validated by the fact that the correlation between price and the series of shale rigs count lagged by four six rockets to 0.97.

This lag is not random but reflects the peculiarities of shale oil industry. More in detail, because of time necessary to put a shale rig in efficiency and its expected lifetime[20], the reaction to a change in crude oil price it takes between three and nine months, while overall production, considering also existing wheels, is even

[20] Production peak is on average reached after one month of operation and productivity stage usually does not exceed one year.

	Z_1	Z_2	Z_3	Z_4	Q
Z_1	1.000	$-.0885$	.0381	$.4260^{***}$	$-.4373^{***}$
Z_2	$-.0885$	1.000	$-.1906^{**}$	$-.5285^{***}$	$.7883^{***}$
Z_3	.0381	$-.1906^{**}$	1.000	$.2048^{***}$	$-.1765^{*}$
Z_4	$.4260^{***}$	$-.5285^{***}$	$.2048^{***}$	1.000	$-.4154^{***}$
Q	$-.4373^{***}$	$.7883^{***}$	$-.1765^{**}$	$-.4154^{***}$	1.000

Table 5: Correlation Matrix of crude oil world production and instrumental variables used to explain it. For off-diagonal elements it is also provided the confidence level of the test for a significant correlation: *** and ** denote statistical significance at the 1% and 5% level respectively, otherwise the correlation is not significant.

Parameter	**Estimate**
Intercept	3.1754***
	(0.2456)
World Active Rigs	−0.1404***
	(0.0216)
World Oil Reserves	3.2319***
	(0.1655)
GDP MENA	−0.1048***
	(0.0131)
SXEP Index	0.1362***
	(0.0279)

Table 6: Results of the estimation of equation (45). The standard error is reported in brackets, while *** denotes statistical significance at the 1% level. The adjusted R^2 and the F-statistic are equal to 0.846 and 235(***) respectively.

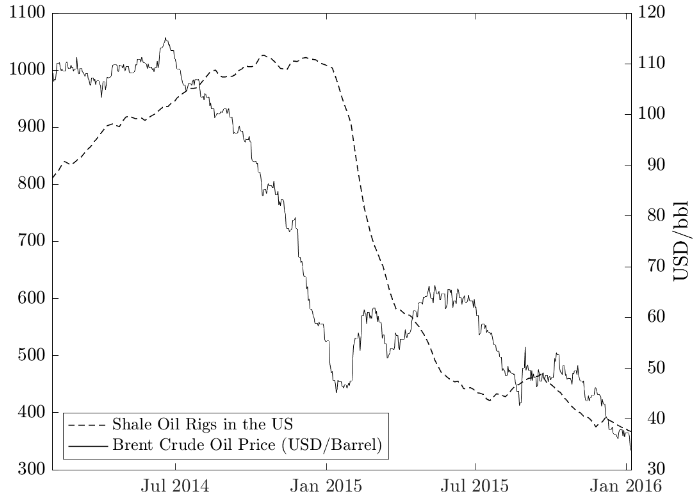

Figure 6: Count of shale oil active rigs in the US (left scale) and Brent crude oil price (right scale).

more gradual Lasky [2016]. This empirical evidence highlights that the possibility for shale oil operators to reduce operations, by avoiding putting in efficiency new rigs, is real and can be seen as mothballing.

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