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AUTHOR
Istemi Berk

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Institute of Energy Economics at the University of Cologne (EWI)
www.ewi.uni-koeln.de

Institute of Energy Economics
at the University of Cologne (EWI)

Alte Wagenfabrik
Vogelsanger Straße 321a
50827 Köln
Germany

Tel.: +49 (0)221 277 29-100
Fax: +49 (0)221 277 29-400
www.ewi.uni-koeln.de

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Istemi Berk*

Institute of Energy Economics, Cologne Graduate School, University of Cologne

Abstract

This paper analyzes the strategic firm behavior within the context of a two-period resource duopoly model in which firms face endogenous intertemporal capacity constraints. Firms are allowed to invest in capacity in between two periods in order to increase their initial endowment of exhaustible resource stocks. Using this setup, we find that the equilibrium price weakly decreases over time. Moreover, asymmetric distribution of initial resource stocks leads to a significant change in equilibrium outcome, provided that firms do not have the same cost structure in capacity additions. It is also verified that if only one company is capable of investment in capacity, the market moves to a more concentrated structure in the second period.

Keywords: Dynamic Duopoly, Cournot Competition, Endogenous Intertemporal Capacity Constraints, Subgame Perfect Nash Equilibrium
JEL-Classification: D43, L13, Q32, Q4

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*Istemi.Berk@ewi.uni-koeln.de, +49 22127729315, Vogelsanger Strasse 321, 50827 Cologne, Germany.

1. Introduction

One of the most important aspects of strategic firm behavior in oligopolistic non-renewable or exhaustible resource markets is the allocation of a finite resource stock over time. The problem of resource allocation becomes more complicated once firms seize the opportunity to increase the resource base. In this case, in addition to the production decisions, firms also need to choose the optimal amount of resource additions over time.

In order to address the question of how firms would react under endogenous capacity constraints, we study a resource duopoly model with two firms, competing in quantity for two consecutive periods. At the beginning of the first period, each firm is endowed with a fixed amount of exhaustible resource stock and is then allowed to invest in capacity in between the two periods of production in order to increase its resource stock. Thus, their 2^{nd} period capacity constraints become endogenous. With this setup, we find that the equilibrium price weakly decreases over time. Moreover, asymmetric distribution of initial resource stocks leads to a significant change in equilibrium outcome, provided that firms do not have the same cost structure in capacity additions. It is also verified that if only one company is capable of investment in capacity, the market moves to a more concentrated structure in the second period.

Apart from the mainstream economic growth literature dealing with the optimal depletion of exhaustible resources following Hotelling (1931)[1], there has been a plethora of works that deal with the microeconomic structure of resource markets. Salant (1976) proposes a cartel with a competitive fringe model to explain the world oil market and suggests that a cartel would restrict its supply, leading to a monotonic increase in prices, until it takes over the whole market and the competitive fringe exhausts its resources. Gilbert (1978) extends the study of Salant (1976) with a Stackelberg model under the price and quantity leadership of the cartel and confirms that the price would increase until the reserves of the fringe firms are exhausted. Another dynamic oligopolistic market is examined by the study of Lewis and Schmalensee (1980), which proposes that any firm having a greater initial resource endowment will produce more at each period of the game. Eswaran and Lewis (1984) extend the oligopoly model such that each firm has an initial share of the common reserve. The authors find that given uneven distribution of the shares among firms, industry extraction is inefficient as it is not cost minimizing.

In his famous work entitled “A Theory of ‘Oil’igopoly: Cournot Equilibrium in Exhaustible Resource Markets with Fixed Supplies”, Loury (1986) proposes a non-cooperative Cournot

[1]Seminal works in this stream of literature are as follows: Solow (1974), Dasgupta and Heal (1974), Stiglitz (1974), Loury (1978), Pindyck (1978).

oligopoly model. He finds that marginal returns on resource stocks are inversely related to players' initial resource endowments and that aggregate production decreases over time. He also suggests that firms with smaller resource stock exhaust their stocks at the same time as larger stock firms. Polasky (1992) extends the model of Loury (1986) by introducing different extraction costs among the firms and empirically testing the model. Gaudet and Long (1994) criticize the assumptions thought to be necessary by Loury (1986) in order to achieve a unique equilibrium for the game with uneven distribution of initial resource stocks among players. Contrary to Loury (1986), they suggest that exhaustion of resources in finite time is not a necessary condition for equilibrium. Later, Salo and Tahvonen (2001) contributed to this stream of literature by considering the economic depletion of resources instead of the physical depletion. They find, contrary to the literature, that the degree of concentration in supply would decline such that the market would head in the direction of more competitive rather than monopolistic. On the other hand, more recently Benchekroun et al. (2009) and Benchekroun et al. (2010) suggest, in accordance with Loury (1986), that the oligopolistic market, in which players have different initial resource stocks and different cost structures, would move towards a cartel with a competitive fringe structure as low-cost deposits are exhausted.

This article also relates to the literature on strategic firm behavior under capacity constraints. Pioneering works in this stream are Levitan and Shubik (1972) and Osborne and Pitchik (1986), both of which are based on price competition under exogenous capacity constraints. Important contributions are made, among others, by Bikhchandani and Mamer (1993), Gabszewicz and Poddar (1997), Besanko and Doraszelski (2004) and Laye and Laye (2008). Moreover, Saloner (1987) introduces intertemporal production decisions with a two-period Cournot duopoly, which is later extended by Pal (1991) with the inclusion of cost differences.

The primary contribution of this paper is that it is among the firsts to subject dynamic duopoly markets to endogenous intertemporal capacity constraints. In fact, the author is only aware of two papers that address the strategic firm decisions under a two-period duopoly with exogenous intertemporal capacity constraints, namely Biglaiser and Vettas (2004) and van den Berg et al. (2012), examining price and quantity competition, respectively. We extend the model of van den Berg et al. (2012), which most resembles the current study, by relaxing the assumption of exogenous capacity constraints. Thus, in our setting, besides the quantity competition firms also enter into a rivalry in capacity investments, which leads to endogenous capacity constraints. In contrast to van den Berg et al. (2012)'s main finding that the price weakly increases over time, we are able to show that the price decreases with endogenous capacity constraints. This would explain the temporary downward price trends experienced occasionally in most exhaustible resource markets. Thus, the author believes that the model presented in this study better explains the stylized characteristics of such markets.

The organization of the current paper is as follows: Section 2 introduces the model. Section 3 solves the model using the Subgame Perfect Nash Equilibrium concept and provides major results. Section 4 presents oil market interpretation of the model. Welfare analysis is conducted in Section 5. Finally, Section 6 concludes.

2. Model

This article proposes a resource duopoly model with two firms, $i = 1, 2$, competing in quantity for two consecutive periods, $t = 1, 2$. At the beginning of the first period ($t = 0$), each firm is endowed with a fixed amount of exhaustible resource, $R_{i,0} \geq 0$, which can be increased to a cumulative recoverable resource, $(R_{i,0} + R_{add,i}) \in [R_{i,0}, R_{max}]$, where $R_{add,i}$ is the additions to the resource base (capacity additions) of firm i and R_{max} is finite. Thus, firms can endogenize their 2^{nd} period capacity by simultaneously choosing $R_{add,i}$ in the interim period at a cost of x_i, i.e., capacity investment. This creates a three-stage game as depicted in Figure 1.

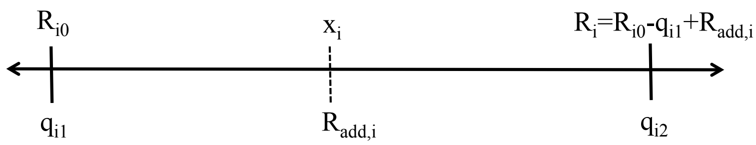

Figure 1: Structure of the Game

In Figure 1, $q_{i,1}$ is the quantity decision of firm i in the first stage (1^{st} period of production) subject to its initial resource endowment ($R_{i,0}$), $R_{add,i}$ is the decision made on capacity addition in the second stage (in between the two periods of production) at a cost of x_i, and finally $q_{i,2}$ is the quantity decision of firm i in the third stage (2^{nd} period of production) subject to its remaining endogenous capacity defined by the following equation:

$$R_i = R_{i,0} - q_{i,1} + R_{add,i}. \tag{1}$$

Assumption 1. *Initial resource endowment for each firm lies in the following range:*[2]

$$\frac{\alpha_1 A + \alpha_3 R_{j,0}}{\alpha_4 - \alpha_2} < R_{i,0} < \frac{(\alpha_4 - 3\alpha_8)A - 3\alpha_{10} R_{j,0}}{3\alpha_9} \quad \textit{for} \quad i, j \in 1, 2 \quad \textit{and} \quad i \neq j$$

The upper bound of the interval provided by Assumption 1 guarantees that the second period capacity constraint for each firm is binding; thus, at equilibrium firms invest in capacity $R_{add,i} > 0$ for $i \in \{1, 2\}$. If this part of the assumption is violated, the problem becomes less interesting as it reduces to the typical dynamic Cournot game with exogenous intertemporal constraints, in which equilibrium is achieved without positive capacity investments. This case is in fact already considered in van den Berg et al. (2012). The lower bound, moreover, guarantees that each firm would carry some of its initial resource endowment over to the second period. If violated, the capacity constraints are no longer intertemporal. In this case, each firm uses up all of its initial capacity in the first period, generates new capacity in the interim period and uses it again in the second period. Since the focus of this paper is the intertemporal allocation of the endogenous resource, a lower bound of Assumption 1 is also necessary.

We, furthermore, assume that the costs of exploring initial resource stock and resource extraction are sunk and therefore do not have a role in the model. The inverse demand function for each period is as follows:

$$P_t = P_t(Q_t) = A - Q_t,$$

where A captures the market size and $Q_t = q_{i,t} + q_{j,t}$ for $i, j \in \{1, 2\}$ and $i \neq j$. Moreover, we define the capacity addition cost function as:

$$x_i = a_i \times {R_{add,i}}^2, \tag{2}$$

where a_i ($\in \mathbb{N}_+$) is a finite constant that captures the "reverse efficiency" (or the cost) of capacity investments such that, as it becomes larger, capacity additions become more costly.[3]

[2] The α's are defined on page 12 by Proposition 1.

[3] We would have assumed a general functional form for capacity addition cost, x_i, that is convex in $R_{add,i}$, yet the functional form provided is tractable as its first derivative is linear.

3. Subgame Perfect Nash Equilibrium

We employ the Subgame Perfect Nash Equilibrium (SPNE, hereafter) concept, which suggests that the strategy of each player at each instant of time is a function of the prior decisions made by both itself and its rival. Therefore, for any state of the game at the beginning of the 2^{nd} period $z(q_{i,1}, q_{j,1}, R_{add,i}, R_{add,j})$, which is the result of the 1^{st} and interim period decisions, firm i will solve the following maximization problem given firm j's production decision:

$$\max_{q_{i,2}} \ \pi_{i,2} = q_{i,2} \ P_2(q_{i,2}, q_{j,2}) - x_i(R_{add,i})$$
$$\text{subject to}$$
$$0 \le q_{i,2} \le R_i,$$

where, recall that, R_i is the 2^{nd} period capacity constraint defined by Equation 1. The resulting best response correspondence for firm i in the 2^{nd} period, $\sigma_{i,2}(z) : [0, R_j] \rightarrow [0, R_i]$, will be as follows:

$$\sigma_{i,2}(q_{j,2}) = \begin{cases} R_i & \text{if} \quad 0 \le R_i \le \frac{A-q_{j,2}}{2} \\ \max\left(0, \frac{A-q_{j,2}}{2}\right) & \text{otherwise.} \end{cases}$$

Equilibrium strategies for firm i are given by the function $f_i^*(z)$ and defined as follows:

$$f_i^*(z) = \begin{cases} \frac{A}{3} & \text{if} \quad R_i, R_j > \frac{1}{3} \\ \frac{A-R_j}{2} & \text{if} \quad R_i > \frac{A-R_j}{2} \text{ and } R_j \le \frac{A}{3} \\ R_i & \text{if either } R_i \le \frac{A}{3} \text{ and } R_j > \frac{A-R_1}{2} \text{ or } R_i \le \frac{A-R_j}{2} \text{ and } R_j \le \frac{A-R_i}{2}. \end{cases} \tag{3}$$

Region	$q_{1,2}^*$	$q_{2,2}^*$	R_1	R_2
I	A/3	A/3	$> A/3$	$> A/3$
II	R_1	$\frac{A-R_1}{2}$	$\le A/3$	$> \frac{A-R_1}{2}$
III	$\frac{A-R_2}{2}$	R_2	$> \frac{A-R_2}{2}$	$\le A/3$
IV	R_1	R_2	$\le \frac{A-R_2}{2}$	$\le \frac{A-R_1}{2}$

Table 1: Second Period Possible Equilibrium Outcomes

There may exist four possible Nash equilibria for the second-period subgame $(q_{1,2}^*, q_{2,2}^*)$, which satisfy both $\sigma_{1,2}(q_{2,2}^*) = q_{1,2}^*$ and $\sigma_{2,2}(q_{1,2}^*) = q_{2,2}^*$ as provided in Table 1. Since in Region I the 2^{nd} period capacities of both firms are non-binding, each firm chooses the Cournot outcomes and ends up with a residual amount left 'unproduced' in the resource base. Regions II and III correspond to the outcomes when only one firm has a binding capacity, firm 1 and firm 2, respectively. And, finally, in Region IV both firms have binding capacities, thus producing whatever their capacity allows. Given Assumption 1, the equilibrium can not occur in Regions I, II and III (See Lemma 1).

Lemma 1. *Given Assumption 1, each firm chooses the second period equilibrium quantity to be:*

$$\begin{gathered} q^*_{i,2} = R_i = R_{i,0} - q_{i,1} + R_{add,i} \\ \textit{for} \quad i = 1,2 \quad \textit{where} \quad R_i, R_j \leq A/3 \end{gathered} \tag{4}$$

Proof. Firms would deviate from this equilibrium if and only if at least one of them, say firm 1, has non-binding capacity in the second period. Given Assumption 1, this can arise due to either the firm investing too much in the capacity in the interim period and thus generating more capacity addition than it needs, or the firm producing too little in the first period thus saving the capacity for the second period in order to end up with the Cournot outcome. Let us analyze these two cases:

i. Let us assume that firm 1 chooses to over-invest in capacity in the interim period to end up with the non-binding second period capacity constraint and thus produce the Cournot quantity. Since the capacity addition cost function is strictly increasing in $R_{add,1}$, the firm can decrease the capacity addition, and hence the cost, until the second period capacity reaches the threshold value of $\overline{R}_1 = A/3$, without changing the second period equilibrium strategy of $q^*_{1,2} = A/3$. Once the second period capacity equalizes to $\overline{R}_1$, the firm is in Region IV. Note that the capacity addition decisions in the interim period are being made simultaneously. Thus, there is no first-mover advantage in the game. If this was the case, the outcome may have been different than that proposed here.

ii. Let us assume that firm 1 chooses to produce too little –strictly lower than the Cournot quantity– in the first period to assure non-binding capacity for the second period, i.e., $q_{1,1} < A/3$. This implies that it would not add further capacity in the interim period since it has already ensured the Cournot outcome for the second period, i.e., $R_{add,1} = 0$. First of all, one must note that firm 1 will affect firm 2's decision at this stage of the game if and only if it has a binding capacity. If its capacity constraint is not binding, then firm 2's behavior is left unaltered (firm 2 chooses the optimal quantity given firm 1's production not the capacity). Hence, firm 1 could deviate from this strategy by producing one marginal unit more at the first stage instead of having left over at the third stage. This reallocation continues until the second period capacity of firm 1 becomes binding, i.e., $R_1 \leq \overline{R}_1$.

Moreover, the firm would not choose an equilibrium quantity of zero for the second period, i.e., $q^*_{i,2} = 0$, because it would always have the incentive to generate additional capacity for the second period. ■

Given the 2^{nd} period equilibrium provided in Equation (4), firm i will subsequently choose the capacity additions with the following maximization problem:

$$\max_{R_{add,i}} \ \pi_{i,2} = q^*_{i,2}\ P_2(q^*_{i,2}, q^*_{j,2}) - x_i(R_{add,i}), \tag{5}$$

where $q^*_{i,2}$ and $q^*_{j,2}$ represent the 2^{nd} period equilibrium quantities of firms i and j, respectively. Following the maximization problem in Equation (5), the best response correspondence for the interim period capacity addition decision, γ_i, for firm i is as follows:

$$\gamma_i(R_{add,j}) = \begin{cases} 0 & \text{if } \ R_{add,j} > A + 2q_{i,1} + q_{j,1} - 2R_{i,0} - R_{j,0} \\ \frac{A+2q_{i,1}+q_{j,1}-2R_{i,0}-R_{j,0}-R_{add,j}}{2+2a_i} & \text{otherwise.} \end{cases}$$

Region	$R^*_{add,1}$	$R^*_{add,2}$
A	0	0
B	$\frac{A+2q_{1,1}+q_{2,1}-2R_{1,0}-R_{2,0}}{2+2a_1}$	0
C	0	$\frac{A+2q_{2,1}+q_{1,1}-2R_{2,0}-R_{1,0}}{2+2a_2}$
D	$\frac{A(1+2a_2)+(3+4a_2)q_{1,1}+2a_2q_{2,1}-(4a_2+3)R_{1,0}-2a_2R_{2,0}}{4a_1a_2+4a_1+4a_2+3}$	$\frac{A(1+2a_1)+(3+4a_1)q_{2,1}+2a_1q_{1,1}-(4a_1+3)R_{2,0}-2a_1R_{1,0}}{4a_1a_2+4a_1+4a_2+3}$

Region	Parameter Conditions
A	$A + 2q_{1,1} + q_{2,1} < 2R_{1,0} + R_{2,0}$ $A + 2q_{2,1} + q_{1,1} < 2R_{2,0} + R_{1,0}$
B	$A + 2q_{1,1} + q_{2,1} \geq 2R_{1,0} + R_{2,0}$ $(1 + 2a_2)A + (3 + 4a_2)q_{1,1} + 2a_2q_{2,1} < (3 + 4a_2)R_{1,0} + 2a_2R_{2,0}$
C	$(1 + 2a_1)A + (3 + 4a_1)q_{2,1} + 2a_2q_{1,1} < (3 + 4a_1)R_{2,0} + 2a_1R_{1,0}$ $A + 2q_{2,1} + q_{1,1} \geq 2R_{2,0} + R_{1,0}$
D	$(1 + 2a_2)A + (3 + 4a_2)q_{1,1} + 2a_2q_{2,1} \geq (3 + 4a_2)R_{1,0} + 2a_2R_{2,0}$ $(1 + 2a_1)A + (3 + 4a_1)q_{2,1} + 2a_1q_{1,1} \geq (3 + 4a_1)R_{2,0} + 2a_1R_{1,0}$

Table 2: Interim Period Possible Equilibrium Outcomes

The corresponding possible Nash equilibria, which satisfy $\gamma_1(R^*_{add,2}) = R^*_{add,1}$ and $\gamma_2(R^*_{add,1}) = R^*_{add,2}$, for the subgame at the interim period are provided in Table 2. Region A corresponds to the equilibrium in which none of the firms generate additional capacities for the second period. Regions B and C are the regions in which firm 1 and firm 2, respectively, choose not to add capacity. Finally, Region D represents the equilibrium with positive amount of capacity additions for both firms. Given Assumption 1 and Lemma 1, Lemma 2 will rule out the equilibria in regions A, B and C (See Lemma 2).

Lemma 2. *Interim period equilibrium capacity addition for each firm, $i = 1, 2$, is as follows:*

$$R^*_{add,i} = \frac{A(1+2a_j) + (3+4a_j)q_{i,1} + 2a_j q_{j,1} - (3+4a_j)R_{i,0} - 2a_j R_{j,0}}{4a_i a_j + 4a_i + 4a_j + 3}$$
$$\textit{where} \quad (3+4a_j+2a_i)(R_{i,0}-q_{i,1}) + (3+4a_i+2a_j)(R_{j,0}-q_{j,1}) \leq (2+2a_i+2a_j)A. \tag{6}$$

Proof. Given the best response correspondence, we have 4 different equilibria for the interim period subgame as provided in Table 2. The equilibrium can not occur in Regions A, B and C because:

i. Parameter conditions in Region A together suggest the following:

$$\frac{2A}{3} < (R_{1,0} - q_{1,2}) + (R_{2,0} - q_{2,2})$$

since the capacity addition for each firm in this region is zero, which, given Lemma 1, follows directly as:

$$q^*_{1,2} + q^*_{2,2} > \frac{2A}{3}.$$

This inequilibrium can occur only if at least one of the firms has non-binding capacity in the second period and produces an amount larger then the Cournot outcome. This contradicts Assumption 1.

ii. The equilibrium outcomes in Regions B and C suggest that one firm chooses not to invest in capacity additions in the interim period. Recall that the decisions at this stage are held simultaneously. Thus, this case can occur only if the firm ensures the Cournot quantity for the second period. Given Assumption 1, this can arise if and only if its first period supply is strictly lower than the Cournot quantity. This case has already been eliminated by Lemma 1.

■

Using equilibrium outcomes in the 2^{nd} and the interim periods, $q^*_{i,2}$ and $R^*_{add,i}$ defined by Equations (4) and (6), the game to a one-period optimization in which firm i only chooses the 1^{st} period quantity. The maximization problem is defined as follows:

$$
\begin{aligned}
&\max_{q_{i,1}} \ \Pi_i = \pi_{i,1}(q_{i,1}, q_{j,1}) + \pi_{i,2}(q^*_{i,2}, q^*_{j,2}, x_i(R^*_{add,i})) \\
&\text{subject to} \quad q_{i,1} + q^*_{i,2} \leq R_{i,0} + R^*_{add,i},
\end{aligned} \tag{7}
$$

where $\pi_{i,1}$ and Π_i are firm i's first period profit and reduced profit functions, respectively.[4] Consequently, given Lemma 1 and Lemma 2, the best response correspondence for firm i in the 1^{st} period, $\sigma_{i,1} : [0, R_{j,0}] \rightarrow [0, R_{i,0}]$, will be as follows:

$$
\sigma_{i,1} = \begin{cases} \frac{\beta_1 A - \beta_2 q_{j,1} + \beta_3 R_{i,0} + \beta_4 R_{j,0}}{\beta_5} & \text{if } max\left\{ \frac{-\beta_6 A + \beta_7 q_{j,1} - \beta_8 R_{j,0}}{\beta_9}, \frac{\beta_6 A - \beta_7 q_{j,1} + \beta_8 R_{j,0}}{\beta_{10}}, \frac{\beta_{11} A - \beta_{12} q_{j,1} + \beta_{13} R_{j,0}}{\beta_{14}} \right\} \leq R_{i,0} \leq \frac{\beta_{15} A + \beta_{16} q_{j,1} - \beta_{17} R_{j,0}}{\beta_{10}} \\ R_{i,0} & \text{if } \ R_{i,0} < \frac{\beta_6 A - \beta_7 q_{j,1} + \beta_8 R_{j,0}}{\beta_{10}} \\ 0 & \text{if } \ q_{j,1} > \frac{\beta_6 A + \beta_9 R_{i,0} + \beta_8 R_{j,0}}{\beta_7}, \end{cases}
$$

where

$$
\begin{aligned}
\beta_1 &= 8a_i^2(1 + a_j) + 16a_i(1 + a_j)^2 + (3 + 4a_j)^2 \\
\beta_2 &= 24a_i(1 + a_j)(1 + 2a_j) + 16a_i^2(1 + a_j)(1 + 2a_j) + (3 + 4a_j)^2 \\
\beta_3 &= 16a_i^2(1 + a_j)(1 + 2a_j) + (3 + 4a_j)^2 \\
\beta_4 &= 8(1 + a_i)a_j(1 + a_j) \\
\beta_5 &= 2(1 + a_i)(3 + 4a_j)(3 + 4a_j + 8a_i(1 + a_j)) \\
\beta_6 &= 8a_i^2(1 + a_j) + 16a_i(1 + a_j)^2 + (3 + 4a_j)^2 \\
\beta_7 &= (3 + 4a_i)^2 + 24a_j(1 + a_i)(1 + 2a_i) + 16a_j^2(1 + a_i)(1 + 2a_i) \\
\beta_8 &= 16a_i a_j(1 + a_i)(1 + 2a_i) \\
\beta_9 &= 2a_i(8a_i(1 + a_j)(1 + 2_a j) + (3 + 4a_j)^2) \\
\beta_{10} &= 2a_i(3 + 4a_j + 4a_i(1 + a_j))^2 \\
\beta_{11} &= 3a_i(5 + 6a_i) - 4a_j(1 + a_i)(3 + 2a_i) - 16a_j^2(1 + a_i)(1 + 2a_i) \\
\beta_{12} &= 3(a_i(3 + 4a_i) + 4a_j(1 + a_i)(3 + 8a_i) + 16a_j^2(1 + a_i)(1 + 2a_i)) \\
\beta_{13} &= 12a_j(1 + a_j)(3 + 4a_j + a_i(7 + 8a_j)) \\
\beta_{14} &= 6a_i(3 + 4a_j + 4a_i(1 + a_j)) \\
\beta_{15} &= 3 + 4a_j + 2a_i(8 + 10a_j + a_i(7 + 8a_j))) \\
\beta_{16} &= 9 + 12a_j + 2a_i(3 + 2a_i)(5 + 6a_j) \\
\beta_{17} &= (1 + a_i)(9 + 12a_j 4a_i(6 + 7a_j)).
\end{aligned}
$$

The quantities $(q^*_{i,1}, q^*_{j,1})$ are the Nash equilibrium of the reduced game if and only if $q^*_{i,1} \in \sigma_{i,1}(q^*_{j,1})$ and $q^*_{j,1} \in \sigma_{j,1}(q^*_{i,1})$. Lemma 3 provides the unique Subgame Perfect Nash Equilbrium of the reduced game.

[4] Please note that discount factor assumed to be unity for simplicity.

Lemma 3. *Nash equilibrium of the reduced game for firm i is as follows:*

$$\begin{aligned}
q^*_{i,1} &= \tfrac{\alpha_1 A + \alpha_2 R_{i,0} + \alpha_3 R_{j,0}}{\alpha_4} \quad \textit{for} \quad R_{i,0} > \tfrac{\alpha_1 A + \alpha_3 R_{j,0}}{\alpha_4 - \alpha_2} \\
& \textit{where;} \\
\alpha_1 &= 32a_i^2(1+a_j)(1+6a_j+6a_j^2) + 4a_i(1+a_j)(15+88a_j+88a_j^2) \\
& \quad +(3+4a_j)(9+50a_j+40a_j^2) \\
\alpha_2 &= 4a_i(1+a_j)(27+60a_i+32a_i^2+16(1+a_i)(6+7a_i)a_j+16a_j^2(5+11a_i+6a_i^2)) \\
\alpha_3 &= -2a_j(3+4a_i+4a_j+4a_ia_j)(9+8a_i+8a_j+8a_ia_j) \\
\alpha_4 &= 64a_i^3(1+a_j)(1+2a_j)(5+6a_j) + 48a_i(1+a_j)(9+34a_j+28a_j^2) \\
& \quad +32a_i^2(1+a_j)\big(21+8a_j(9+7a_j)\big) + (3+4a_j)\big(27+4a_j(27+20a_j)\big).
\end{aligned} \tag{8}$$

Proof. The other two possible equilibrium strategies for firm i at this stage are [i] $q^*_{i,1} = 0$ and [ii] $q^*_{i,1} = R_{i,0}$. Let us explain why the firm would not choose these two strategies:

i. Let us assume that in the first period the firm chooses to produce 0 and save all of its initial resource for the second period. Choosing zero production quantity leads to monopoly prices since the only supplier will be the rival. It is a fact that in the second period the firm will not be a monopoly because even if the rival supplies all its initial resource endowment in the first period, it still has an incentive to invest in capacity and to generate new capacity for the second period. Thus, the second period price will be less than the monopoly price. In this case, the firm would enjoy monopoly prices in the first period by reallocating its capacity such that it would increase the production in the first period without changing the production in the second period.

ii. Firm i will choose the first period quantity to be equal to its initial resource endowment if and only if $R_{i,0} \leq \frac{\alpha_1 A + \alpha_3 R_{j,0}}{\alpha_4 - \alpha_2}$. Yet, Assumption 1 excludes this.

■

Following Lemma 1 and Lemma 2, the Nash equilibrium of the reduced game $(q^*_{i,1}, q^*_{j,1})$, defined by Lemma 3, leads to the Sub-game Perfect Nash Equilibrium of the entire game, which is defined by Proposition 1.

Proposition 1. *The Sub-game Perfect Nash Equilibrium of the entire game is unique and defined as follows:*

$$
\begin{aligned}
(q^*_{i,1}, R^*_{add,i}, q^*_{i,2}) \; &= \left(\tfrac{\alpha_1 A+\alpha_2 R_{i,0}+\alpha_3 R_{j,0}}{\alpha_4}, \tfrac{\alpha_5 A+\alpha_6 R_{i,0}+\alpha_7 R_{j,0}}{\alpha_4}, \tfrac{\alpha_8 A+\alpha_9 R_{i,0}+\alpha_{10} R_{j,0}}{\alpha_4}\right), \\
&\textit{where} \\
\alpha_1 &= 32a_i^2(1+a_j)(1+6a_j+6a_j^2)+4a_i(1+a_j)(15+88a_j+88a_j^2) \\
&\quad +(3+4a_j)(9+50a_j+40a_j^2) \\
\alpha_2 &= 4a_i(1+a_j)(27+60a_i+32a_i^2+16(1+a_i)(6+7a_i)a_j+16a_j^2(5+11a_i+6a_i^2)) \\
\alpha_3 &= -2a_j(3+4a_i+4a_j+4a_ia_j)(9+8a_i+8a_j+8a_ia_j) \\
\alpha_4 &= 64a_i^3(1+a_j)(1+2a_j)(5+6a_j)+48a_i(1+a_j)(9+34a_j+28a_j^2) \\
&\quad +32a_i^2(1+a_j)\big(21+8a_j(9+7a_j)\big)+(3+4a_j)\big(27+4a_j(27+20a_j)\big) \\
\alpha_5 &= 2\big[8a_i^2(1+a_j)(1+4a_j)(5+6a_j)+(1+a_j)(3+4a_j)(9+40a_j) \\
&\quad +a_i\big(66+4a_j(107+2a_j(89+44a_j))\big)\big] \\
\alpha_6 &= -\big(3+4a_j+4a_i(1+a_j)\big)\big(27+4a_j(27+20a_j)+4a_i(9+8a_2(4+3a_j))\big) \\
\alpha_7 &= -\big(3+4a_j+4a_i(1+a_j)\big)\big(4a_j(9+10a_j+2a_i(5+6a_j))\big) \\
\alpha_8 &= \big(3+4a_j+4a_i(1+a_j)\big)\big(9+8a_j(6+5a_j)+4a_i(3+2a_j(7+6a_j))\big) \\
\alpha_9 &= \big(3+4a_j+4a_i(1+a_j)\big)\big(4a_i\big(9+12a_i(1+a_j)(1+2a_j)+10a_j(3+2a_j)\big)\big) \\
\alpha_{10} &= -(3+4a_j+a_i(1+a_j))(2(3+4a_i)a_j(3+4a_j))
\end{aligned}
\tag{9}
$$

for

$$
\frac{\alpha_1 A+\alpha_3 R_{j,0}}{\alpha_4-\alpha_2} < R_{i,0} < \frac{(\alpha_4-3\alpha_8)A-3\alpha_{10}R_{j,0}}{3\alpha_9}.
$$

Proof. Nash equilibrium of the reduced game, provided by Lemma 3, corresponds one-to-one with the SPNE of the entire game. Moreover, the parameter constraints provided by Lemma 1, Lemma 2 and Lemma 3 restrict our attention to only one region, which is disjoint to the other excluded regions. Thus, given the interval for the initial resource endowments of each firm, the SPNE defined by Proposition 1 is unique. ∎

Note that the equilibrium in Proposition 1 is valid only for the initial resource endowments that lie in the provided interval. With this interval, we restrict our attention to the equilibrium in which both firms would have positive capacity additions and positive supplies in both periods. As the upper bound of this range is approached, the second period reduces to the unconstrained Cournot game in which the equilibrium is achieved without capacity additions, since the capacity constraints become non-binding.

Proposition 2. *The equilibrium price, P^*_t, weakly decreases over time.*

Proof. Given the interval for initial resource endowments of each firm, we can verify for any combination of (a_i, a_j) that $Q_1^* \leq Q_2^*$, where $Q_t^* = q_{1,t}^* + q_{2,t}^*$. Since the inverse demand function does not change over time, i.e., $P_t = A - Q_t$, the equilibrium price in the first period is larger than or equal to the second period price, $P_1^* \geq P_2^*$. ■

Proposition 2 contradicts Hotelling-based reasoning, which states that the scarcity rent of the exhaustible resources would cause the prices to increase gradually (Hotelling (1931)). Yet, this reasoning is based on the assumption of a fixed amount of initial resource endowments. Thus, the result proposed by Proposition 2 is due to the endogenous capacity constraints. This result, in fact, captures the short-term stylized characteristics of exhaustible resource markets in which price drops are observed from time to time. For instance, exploration of new oil reserves would lead to declining prices as a result of supply enhancements. Proposition 2 may not be applicable if this model is extended to an infinite time horizon since in this case, the capacity addition cost function should have a different structure, capturing the fact that it gets harder to add capacity as the cumulative capacity addition increases.

Proposition 3. *Given a fixed aggregate initial resource endowment, $S_0 = R_{i,0} + R_{j,0}$:*

i. if $a_i = a_j$, an increase or decrease in $|R_{i,0} - R_{j,0}|$ leads to no change in equilibrium price.

ii. if $a_i > a_j$, the equilibrium price in both periods increases (decreases) as the share of $R_{j,0}$ relative to $R_{i,0}$ increases (decreases).

Proof. Let us assume a fixed amount of aggregate initial resource, $S_0 = R_{i,0} + R_{j,0}$. For $a_i = a_j$, total amount of supply in both periods will be a function of only the aggregate initial resource endowment, i.e., $Q_t^*(S_0)$. Thus, given a fixed S_0, a change in $|R_{i,0} - R_{j,0}|$ would not affect the outcome. Yet, when $a_i \neq a_j$, we can verify that an uneven distribution of the fixed aggregate initial resource stock among firms would lead to a significant change in equilibrium supply. More specifically, we can verify that for $a_i > a_j$, an increase in $R_{j,0}$ relative to $R_{i,0}$ leads to a decrease in equilibrium supply in both periods, Q_1^* and Q_2^*. ■

Proposition 3 suggests that if the firms are symmetric in their cost functions, any asymmetric distribution in reserves do not affect the equilibrium outcomes. Moreover, if firms have different cost parameters, $a_i \neq a_j$, equilibrium price increases due to a decrease in equilibrium quantity when the distribution is altered in favor of the more efficient firm, i.e., the one with lower a. The equilibrium price, on the other hand, would decline if the asymmetry is in favor of the less efficient firm, i.e., the one with higher a. This is an expected result since if one firm is more efficient in capacity addition, it would become more dominant in the second period, leading to a more concentrated market structure and eventually to an increase in prices. On the other hand, distribution of initial resource stock in favor of the less efficient firm would offset the advantage of a more efficient firm leading to a more competitive market structure.

Proposition 4. *At equilibrium,*

i. if $R_{i,0} > R_{j,0}$*, then, ceteris paribus,* $q^*_{i,t} > q^*_{j,t}$ *and* $R^*_{add,i} < R^*_{add,j}$ *for* $i, j \in \{1, 2\}$*,* $i \neq j$ *and* $t \in \{1, 2\}$*.*

ii. $\frac{\partial q^*_{i,t}}{\partial R_{i,0}} > 0$*,* $\frac{\partial q^*_{j,t}}{\partial R_{i,0}} < 0$*,* $\frac{\partial R^*_{add,i}}{\partial R_{i,0}} < 0$ *and* $\frac{\partial R^*_{add,j}}{\partial R_{i,0}} > 0$ *for* $i, j \in \{1, 2\}$*,* $i \neq j$ *and* $t \in \{1, 2\}$*.*

Proof. The proof follows directly from the first derivatives of the corresponding continuous functions, i.e. $q^*(.)$ and $R^*_{add}(.)$, with respect to the initial resource endowments. ■

Proposition 4 implies, not surprisingly, that the firm with a greater initial resource endowment would supply more in both periods and generate smaller additional capacity, all else being equal. Moreover, initial resource endowment of a firm has a positive effect on its supplies and a negative effect on the supplies of rival firm in both periods. Finally, initial endowment has negative and positive effects on the capacity additions of the firm itself and its rival, respectively.

Proposition 5. *At equilibrium,*

i. if $a_i < a_j$ *then, ceteris paribus,* $q^*_{i,t} > q^*_{j,t}$ *and* $R^*_{add,i} > R^*_{add,j}$*for* $i, j \in \{1, 2\}$*,* $i \neq j$ *and* $t \in \{1, 2\}$*.*

ii. $\frac{\partial q^*_{i,t}}{\partial a_i} < 0$*,* $\frac{\partial q^*_{j,t}}{\partial a_i} > 0$*,* $\frac{\partial R^*_{add,i}}{\partial a_i} < 0$ *and* $\frac{\partial R^*_{add,j}}{\partial a_i} > 0$ *for* $i, j \in \{1, 2\}$*,* $i \neq j$ *and* $t \in \{1, 2\}$*.*

Proof. The proof follows directly from the first derivatives of the corresponding continuous functions, i.e., $q^*(.)$ and $R^*_{add}(.)$, with respect to the cost parameters. ■

Proposition 5 implies that the firm with higher efficiency, or lower cost parameter, will supply more output in both periods and generate larger capacity addition. Moreover, a_i has negative effects on both supply and investment decisions of firm i and positive effects on those of firm j.

4. Oil Market Interpretation: Oil Field Service (OFS) Companies

One of the most important resource markets is, without a doubt, the oil market. The model presented in Section 2 would, therefore, be applicable to this specific market. The initial resource stock of the firms and the investment in capacity additions could refer to the initial recoverable reserves and the reserve growth investments in the oil market, respectively. As is commonly known, the upstream petroleum industry represents a highly concentrated market structure. For instance, in 2004, 81% of the world's proved reserves was controlled by the major National Oil Companies (NOCs) including Saudi Aramco, National Iranian Oil Company, Iraq National Oil Company, Kuwait Petroleum Corporation, Abu Dhabi National Oil Company, PDVSA (National Oil Company of Venezeula) and National Oil Company of Libya (PWC (2005)). Moreover, according to the US Energy Information Administration, in 2011, NOCs accounted for around 55% of global oil supply, while major International Oil Companies (IOCs) were responsible for 27% (EIA (2013)). Thus, it is a reasonable simplification to assume that the current upstream oil industry is dominated by two blocks of companies, i.e., IOCs and NOCs.

Over the last few years, high oil prices, fluctuating around 100$/bbl (well above the maximum marginal costs for producing a barrel of conventional (around 60$) and of unconventional (around 80$) crude oil), have encouraged upstream petroleum companies to increase production. However, in addition to other factors, substantial risks and costs associated with upstream activities, especially exploration and development operations, remain as the main obstacles facing supply enhancements. The excessive profits that the IOCs can extract create an incentive to face these risks and costs; yet NOCs would not be able to invest further in these activities as they may not have the required know-how or may be required to consider other factors, such as maximizing social welfare in the host country. In this respect, Oil Field Service (OFS, hereafter) companies, which specialize in development activities, emerge as business partners for NOCs.

Increasing recoverability of the reserves is one of the main objectives of development activities in the upstream petroleum industry. Reserve growth technologies, such as enhanced or improved oil recovery techniques, would lead to enhancement in supply via increasing the recoverability ratios of the reserves. Therefore, investment in such technologies is of great importance for upstream petroleum companies as well as for the future market structure of the petroleum industry.

In the general model presented in Section 2, we suggest that both firms can generate additional capacity for the second period. The reality, however, may differ. In fact, as previously mentioned, we implicitly assume that one of the firms, i.e., NOC, may not have the necessary know-how or funding opportunity to invest further into increasing the recoverable reserve and instead employs an OFS company, which is specialized in reserve growth technologies. Now let us assume that there are no OFS companies existing in the upstream oil market and that the NOC, which is represented by firm 2, is not capable of capacity investment. This means that for the NOC, the cost parameter is infinitely large and they can not generate additional capacity for the second period. We call this new case "no-OFS".

Proposition 6. *The Nash equilibrium for the no-OFS case is as follows:*

$$\begin{aligned}(q^*_{1,1}, R^*_{add,1}, q^*_{1,2})_{noOFS} &= \left(\tfrac{(5+6a_1)A+2a_1(5+6a_1)R_{1,0}-(2+2a_1)R_{2,0}}{2(1+a_1)(5+6a_1)}, \tfrac{2A-R_{2,0}-2R_{1,0}}{2(1+2a_1)}, \tfrac{(5+6a_1)A+2a_1(5+6a_1)R_{1,0}-(3+4a_1)R_{2,0}}{2(1+a_1)(5+6a_1)}\right)\\ (q^*_{2,1}, R^*_{add,2}, q^*_{2,2})_{noOFS} &= \left(\tfrac{(2+3a_1)R_{2,0}}{5+6a_1},\ 0,\ \tfrac{(3+3a_1)R_{2,0}}{5+6a_1}\right).\end{aligned} \tag{10}$$

Proof. The proof follows directly from the fact that as the cost parameter for the NOC, a_2, approaches infinity, the Nash equilibrium given in Equation (9) will approach the one represented in Equation (10):

$$\lim_{a_2\to\infty} (q^*_{i,1}, R^*_{add,i}, q^*_{i,2})_{General} \to (q^*_{i,1}, R^*_{add,i}, q^*_{i,2})_{noOFS}.$$

Note that given the cost function in Equation (2), $R_{add,i} = (\frac{x_i}{a_i})^{1/2}$ (which satisfies Inada conditions) we make sure that as a_2 approaches infinity, $R_{add,2}$ approaches zero and not a negative value, i.e., $\lim_{a_2\to+\infty} R_{add,2} = 0$ ■

In order to investigate the effects of OFS companies on the market dynamics, we compare the Nash equilibria of both the General and no-OFS cases, represented by Equations (9) and (10), respectively. Let us assume that in the General case each firm has exactly the same capacity addition cost structure, i.e., $a_1 = a_2 = a$. In the no-OFS case, the cost parameter of firm 1, a_1, stays at the same level, while the cost parameter of firm 2, a_2, approaches infinity.

Proposition 7. *The effect of OFS companies on equilibrium supply and capacity additions for $a_1 = a$ and $a_2 \to \infty$:*

i. The quantity supplied by the capable firm, firm 1 (IOC) in our setup, is greater at each instant of time in the no-OFS case:
$q_{1,1,General} \le q_{1,1,noOFS}$ *and* $q_{1,2,General} \le q_{1,2,noOFS}$.

ii. *The quantity supplied by the incapable firm, firm 2 (NOC) in our setup, is lower at each instant of time in the no-OFS case:*
$q_{2,1,General} \geq q_{2,1,noOFS}$ *and* $q_{2,2,General} \geq q_{2,2,noOFS}$.

iii. *Total quantity supplied to the market is greater at each instant of time in the General Case:*
$Q_{t,General} \geq Q_{t,noOFS}$ *where* $Q_t = q_{1,t} + q_{2,t}$ *and* $t = 1, 2$.

iv. *Total capacity addition in the General case is greater:*
$R_{add,total,General} \geq R_{add,total,noOFS}$ *where* $R_{add,total} = R_{add,1} + R_{add,2}$.

v. *The additional capacity generated by the capable firm is greater in the no-OFS case:*
$R_{add,1,General} \leq R_{add,1,noOFS}$.

Proof. The proofs for [*i.*], [*ii.*], [*iii.*], [*iv.*] and [*v.*] follow directly from Proposition 1 and Proposition 6. ■

Proposition 7 implies that the existence of OFS companies leads to a more competitive market structure in the upstream oil industry. The market would move to a more concentrated structure if we only allow for one firm to invest in reserve growth technologies or, in other words, if there were no OFS companies in the market, because the capable firm would supply more and increase its supply periodically. Existence of OFS firms, moreover, has a significant effect on reserve growth investments and, thus, equilibrium capacity additions. As expected, due to the rivalry between firms, total additional capacity generated in the General case is greater than that in no-OFS case. Yet, the additional capacity generated by the capable firm is greater in the no-OFS case. This result emerges possibly due to the fact that in the no-OFS case, capable firm would enjoy higher profits in the 2^{nd} period by increasing its capacity even more.

5. Welfare Analysis

In the previous sections, we derived the Nash equilibrium for the General case (Section 3) and the no-OFS case (Section 4). In this section, we conduct a welfare analysis. At equilibrium, the consumer surplus (CS) is defined as follows:

$$\text{CS}^* = \frac{1}{2}\left[(Q_1^*)^2 + (Q_2^*)^2\right],$$

where Q_1^* and Q_2^* are the equilibrium aggregate supplies in periods 1 and 2, respectively.

Proposition 8. *In both the General and the no-OFS cases, an increase in the initial resource endowment for at least one of the firms leads to a weak increase in consumer surplus.*

Proof. The proof follows directly from the first derivatives of the equilibrium outcomes with respect to $R_{i,0}$ for $i \in 1, 2$. ■

Proposition 8 suggests, not surprisingly, that consumers would benefit from an increase in the availability of the exhaustible resource. This result is in accordance with the previous findings in the literature, such as Gaudet and Long (1994), and with the stylized characteristics of exhaustible resource markets.

Proposition 9. *Given fixed aggregate initial resource endowment,* $S_0 = R_{i,0} + R_{j,0}$*,*

1. *in the General Case,*
   i. *if* $a_i = a_j$*, an increase or decrease in* $|R_{i,0} - R_{j,0}|$ *leads to no change in consumer surplus.*
   ii. *if* $a_i > a_j$*, the consumer surplus increases (decreases) as the share of* $R_{j,0}$ *relative to* $R_{i,0}$ *decreases (increases).*
2. *in the no-OFS Case,*
   for any a_1*, the consumer surplus increases (decreases) as the share of* $R_{1,0}$ *relative to* $R_{2,0}$ *decreases (increases) or as the share of* $R_{2,0}$ *relative to* $R_{1,0}$ *increases (decreases).*

Proof. The proof follows directly using the same reasoning provided in the proof of Proposition 3. ■

Proposition 9 implies, in line with Proposition 3, that if one firm is slightly more efficient than the other, consumer welfare tends to change with the asymmetric distribution of initial resource endowment. Consumer welfare decreases if the asymmetry is in favor of the more efficient firm. On the other hand, if the initial resource distribution is in favor of the less efficient firm, the consumer welfare increases.

The total welfare function in our setting can be defined as follows:

$$\mathrm{W} = \mathrm{TS}_1 + \mathrm{TS}_2 - X = A\big(Q_1^* + Q_2^*\big) - \frac{1}{2}\big[(Q_1^*)^2 + (Q_2^*)^2\big] - \big(a_1 R_{add,1}^2 + a_2 R_{add,2}^2\big),$$

where TS_1 and TS_2 are total surpluses in periods 1 and 2, respectively, and X is the aggregate amount of capacity addition costs. The first-best decisions made on total quantity and capacity addition, which maximize total welfare, are as follows:

$$\begin{aligned} Q_{1,FB} = Q_{2,FB} &= \tfrac{A(a_1+a_2)+2a_1a_2(R_{1,0}+R_{2,0})}{a_1+a_2+4a_1a_2} \\ R_{add,FB} &= \tfrac{(a_1+a_2)(A-R_{1,0}-R_{2,0})}{a_1+a_2+4a_1a_2}. \end{aligned} \tag{11}$$

Proposition 10. *The equilibria in the General case defined by Proposition 1, in the no-OFS case by Proposition 6 and first-best case by Equation 11 reveal the following:*

i. $W_{FB} > W_{General} > W_{noOFS}$,

ii. $Q_{t,FB} > Q_{t,General} > Q_{t,noOFS} \quad for \quad t \in \{1,2\}$,

iii. $R_{add,FB} > R_{add,General} > R_{add,noOFS}$.

Proof. The proof follows directly from the equilibria defined by equations (9), (10) and (11). ■

According to Proposition 10, the total welfare and all three decision variables are the largest in the first-best calculation and smallest in the no-OFS case. We confirm, in line with Proposition 7, that the General case, in which both firms are capable of capacity addition is superior to the no-OFS case.

6. Conclusion

This paper analyzes the strategic firm behavior within the context of a two-period resource duopoly model in which firms face endogenous intertemporal capacity constraints. We find that the equilibrium price weakly decreases over the two periods. This result captures the short-term stylized characteristics of exhaustible resources markets, in which price drops are occasionally observed. For instance, exploration of new oil reserves may lead to declining prices as a result of supply enhancements. Moreover, we show that asymmetric distribution of initial resource stocks leads to a significant change in equilibrium outcome, provided that firms do not have the same cost structure in capacity additions. It is also verified that if only one company is capable of investment in capacity, the market moves to a more concentrated structure in the second period.

We also conduct an oil market interpretation of the general model. For this purpose, we assume that the NOC does not have the necessary know-how or funding opportunities for reserve growth investments. Yet, it can employ an OFS company to compete with the IOC in capacity addition. We find that under the absence of OFS companies, only one firm is capable of increasing the capacity for the second period, thus moving the market towards a more concentrated structure. Therefore, the OFS companies carry significant importance in the upstream petroleum industry. Although the integrated structure of the companies, mostly IOCs, increases the profitability, the increasing role of small independent firms that are specialized only in exploration and production is sustainable only if these small firms are supported by OFS companies in development activities. Hence, promoting specialization in these activities, especially reserve growth technologies, would not only serve as a useful tool to increase the competition but also lead to more recoverable resources.

A possible extension of the model could be the introduction of stochasticity in capacity generation such that the capacity additions would be a result of R&D activity held at a prior stage of the game. Another extension would be to analyze the first-mover advantages in the game. However, these extensions could only be made if one could find a model specification that is sufficiently general but also analytically tractable.

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