Do renewables affect the strategic behavior of OPEC? *

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Abstract

This paper investigates how the production of renewable energy by non-OPEC producers may affect OPEC's strategic behavior. We focus on two OPEC's strategies: (i) set low oil prices (squeeze) or (ii) allow high-cost competitors to remain in the market (accommodate). The results indicate that when efficient non-OPEC producers are price takers the squeeze strategy becomes more attractive for OPEC, especially when they are inefficient in producing renewables and consumers perceive both goods as homogeneous products. In addition, the squeeze strategy induces more production of renewables when its production cost is low. However, if non-OPEC producers can influence price and are also efficient in producing renewable energy, a price war becomes more likely. Finally, we show that the squeeze strategy arises under less demanding conditions when renewables are present than otherwise.

JEL Classification: L12, L71, Q41

Key Words: OPEC; Stackelberg; squeeze and accommodate strategies; product differentiation; renewable energy.

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1. Introduction

During 2008's Global Financial Crisis, global oil supply overtook demand and oil prices started to decline. From that time, the Organization of Petroleum Exporting Countries (OPEC) has coordinated production cuts to accommodate other producers and gain profits.[1] Since 2014, however, OPEC decided to lower prices to increase its market share and drive new non-OPEC oil producers out of business, namely, shale oil producers.[2] However, OPEC has struggled to maintain this strategy due to plummeting profits and competition from non-OPEC producers.

Recently clean energy investment has increased, reaching $333.5 billion globally in 2017, a 3 percent increase relative to 2016. One of the biggest investors is the United States, at $56.9 billion, being also the largest biodiesel in the world, totaling 6 billion liters in 2017.[3] In 2018, Royal Dutch Shell spent over $400 million on a range of acquisitions from solar power to electric car charging points, thus not being limited to renewables such as biofuels, solar and wind.[4] Another Non-OPEC producer which has invested in clean energy is Russia, where hydro-power generation is an important element in ensuring the reliability of its Unified Energy System. In 2020, it owns 102 hydropower plants with a capacity of more than 100 MW which can account for 20.6% of its total electricity production.[5] Excluding hydropower and bioenergy Russia also has other renewable power generation capacity including solar PV, wind and geothermal.

We seek to analyze the effect of clean energy production on OPEC's strategic actions. Specifically, we examine two OPEC's strategies: (i) squeeze, in which OPEC lowers oil prices to force high-cost competitors to exit the market or (ii) accommodate, where OPEC allows high-cost competitors to stay in the industry.

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[1] According to estimates in 2018, 79.4 percent of the proven oil reserves in the world are in OPEC member countries, which is a cartel of 14 major oil exporters, including Saudi Arabia, Iran, and Iraq. For more details see: https://www.opec.org/opec_web/en/data_graphs/330.htm

[2] The price of oil fell from over $100 a barrel to less than $50 a barrel in 2016. For more details see: https://www.nytimes.com/2017/06/15/business/energy-environment/gas-oil-petrol-opec.html

[3] Energy analyst Phil Verleger states that high price of oil will lead to higher demand for biodiesel. Renewable and biodiesel have extended the global refining capacity and fuel supply by around 4 percent. For more details see: https://www.biofuelsdigest.com/bdigest/2018/07/24/200-oil-in-2020-the-impending-energy-crisis-and-biofuels-role-in-relieving-the-refining-capacity-crunch/

[4] Shell ventured into solar energy buying a 43.86 percent stake in Silicon Ranch Corporation and invested in two projects to develop charging stations for electric vehicles across Europe's highways. It has also signed agreements to buy solar power in Britain and developed renewables power grids in Asia and Africa. For more details see: https://www.reuters.com/article/us-shell-m-a/shell-buying-spree-cranks-up-race-for-clean-energy-idUSKBN1FF1A8

[5] Currently, Russia ranks second in the world in terms of hydro-power resources. For more information see: http://www.eng.rushydro.ru/industry/history/

Our study builds on the work developed by Behar and Ritz (2017). They analyze how different fundamental market factors, such as slower global oil demand or greater US shale oil production among others, affect OPEC's strategic behavior (i.e., squeeze or accommodate). Similarly, we follow their simplified assumptions considering a static model. However, we complement their study by examining the effect of production of renewables by an efficient (low-cost) non-OPEC producer on OPEC's strategy and compare our results with those under no production of renewables. We first consider the case in which non-OPEC producers are price takers. In this context, the time structure of the game is the following: first, OPEC decides whether to accommodate or squeeze and, second, the low-cost non-OPEC chooses its renewable production. We also examine a context in which the efficient non-OPEC can influence price. In this case, the structure of the game changes since now the low-cost non-OPEC can also decide whether to accommodate or to squeeze. The surge of US shale as a key global player that can pump even during low oil prices represent this particular case.[6]

We find that when low-cost non-OPEC producers are price takers and their cost of producing renewables is high, the squeeze strategy becomes more attractive for OPEC if consumers perceive oil and renewable energy as homogeneous goods. In this case, renewables do not represent a threat to OPEC. Therefore, squeezing helps OPEC to eliminate inefficient non-OPEC producers and, in addition, it ameliorates the business stealing effect from the efficient non-OPEC which also produces renewables. Furthermore, we find that the squeeze strategy induces more production of renewables if its production cost is sufficiently low and the cost differential between efficient and inefficient producers is small. Hence, an aggressive strategy from OPEC triggers a higher production of renewables, since the efficient non-OPEC can mitigate the losses produced by the squeeze strategy with its profits from the renewable market.

In a more competitive scenario, a price war is likely to occur when low-cost non-OPEC can also influence price. If the production of renewables become inexpensive and less differentiated from oil, we observe that oil producers (OPEC and low-cost non-OPEC) choose the squeeze strategy. The results help us explain the 2019 conflict between US shale and OPEC, as output from US shale oil producers has doubled in the last five years and also the 2020 oil price

[6] In May 2017 to stabilize oil prices OPEC sent a plea to the US to stop pumping so much oil after a flood of supply from US shale producers, supporting the argument that the US production can now affect prices. For more details see:http://money.cnn.com/2017/05/18/investing/opec-oil-prices-us-shale-saudi-arabia/index.html

war between OPEC and Russia.[7] In this setting, the low-cost Non-OPEC chooses to squeeze which induces OPEC to also squeeze and go into a price war. Therefore, renewables that are recently discovered (early stage of the technology and, hence, intermediate or high cost) are less likely to trigger an aggressive strategy from OPEC.

Finally, we compare our findings to the case in which the low-cost non-OPEC does not produce renewables, but it is able to influence prices. We show that the production of renewables makes the squeeze strategy more attractive for the efficient non-OPEC producer relative to the case in which it does not operate in both markets. Hence, the squeeze strategy arises under less demanding conditions when production of renewable energy is allowed. That is, the production of renewable energy, that is perceived as a close substitute for oil, induces OPEC to adopt a more aggressive strategy, which is responded by low-cost non-OPEC producers with the same strategy, ultimately, leading to a price war.

1.1. Literature Review

Huppmann and Holz (2012) argue that since 2008 there has been a change in behavior in the crude oil industry with OPEC having less market power. Several papers analyze OPEC decision, but using different approaches. While some papers state OPEC does not show cartel behavior (Reynolds and Pippenger (2010), Colgan (2014), Kisswani (2016)), others acknowledge OPEC as a cartel but with limited collusion (Almoguera et al. (2011), Huppmann and Holz (2012), Okullo and Reynès (2016)). Huppmann (2013) examines the recent shift in the demand and supply of crude oil market assuming a Stackelberg oligopoly with fringe. Langer et al. (2016) study the shifts of global trade flows and strategic refinery investments in a spatial, game-theoretic partial equilibrium model. Their model considers substitution effects between different types of crude oils and petroleum products to find long-term equilibrium shifts in global trade flows and utilization ratios of different refinery technologies within the US. However, they do not consider the effects of renewable production by non-OPEC members on OPEC's strategic behavior.

Huppmann and Livingston (2015), Fattouh et al. (2016) and Behar and Ritz (2017) study OPEC's strategies and show that OPEC flooded the market with crude in an attempt to defend its market share and to drive out shale producers. Their findings are consistent with numerous other

[7] Gordon Gray, head of oil and gas research at HSBC, confirms that currently the OPEC and the US producers are at a "tug of war." Rising supply of US shale in 2019 could flood markets yet again. For more details see: https://www.wsj.com/articles/opec-vs-shale-the-battle-for-oil-price-supremacy-11555588826

papers (Mănescu and Nuño (2015), Brown and Huntington (2017)). Our paper investigates a similar context but considers that efficient non-OPEC members produce renewables, hence, we are able to provide a different explanation to this observed OPEC's behavior. Ansari (2017) states that the price drop of 2014 to 2016 was most plausibly the result of rising competitiveness of alternative technologies. However, he does not theoretically analyze this idea and only considers OPEC's attempt to defend market shares. Our paper is the first to examine OPEC's strategic behavior when production of renewable energy is in place. Several papers have studied the oil and renewable market separately (Mahapatra and Nanda (2011), Ortiz-Cruz et al. (2012), Wattanatorn and Kanchanapoom (2012)).[8] They mainly focus on whether to invest in oil or renewable energy but do not discuss about the strategic effects of producing in both sectors. Jaakkola (2019) takes into consideration both oil and renewable energy but focuses on a strategic carbon taxation.

Gately (1989) empirically examines the prospects of OPEC in the global oil market by focusing on the differences in behavior of OPEC and non-OPEC members. He argues that OPEC has lost its power in the market, but it is still relevant in determining oil prices. Fattouh and Mahadeva (2013) analyze the evolution of OPEC models and key developments in the oil market, finding that OPEC pricing power varies over time. Fattouh et al. (2016) examines the oil market crisis of 2014, stating uncertainty as the key reason for a policy change. Genc (2017) empirically investigates demand response to crude oil price movements before and after the recent global financial and economic crisis. The above literature, however, do not take into consideration the growing renewable energy sector and its effects on OPEC's selection of strategies.

The structure of the paper is as follows, section 2 presents the model and studies the case in which the low-cost non-OPEC does not influence price. Section 3 considers the case where low-cost non-OPEC can influence price and simultaneously maximizes profits in the oil and renewable sector. Section 4 examines a context in which the low-cost non-OPEC influence price but does not produce renewables. Section 5 provides a discussion of our results and, finally, section 6 concludes.

[8] In addition, Reboredo et al. (2017), using data on the stock market, found consistent evidence of nonlinear causality running from renewable energy indices to oil prices at different time horizons, and mixed evidence of causality running from oil to renewable energy prices.

2. Model

In order to examine OPEC's strategic behavior, we study two different contexts. We first analyze the case in which low-cost non-OPEC are price takers. The second scenario relaxes this assumption and allows for the non-OPEC to also influence price.

2.1. Non-OPEC producers are price takers

We first consider a less competitive scenario where OPEC acts as a Stackelberg leader in the market for oil and the low-cost non-OPEC producer simultaneously maximizes profits in the oil and renewable energy market. In this model, the efficient non-OPEC does not influence price and produces up to its maximum capacity.

We assume that the oil industry is composed of $N + i$ oil producers which consists of OPEC denoted as i, plus N other non-OPEC players. Consider that non-OPEC producers can have either low-cost (L) or high cost (H), where marginal costs are represented by c_L^O and c_H^O respectively, $c_H^O > c_L^O$ and superscript O denotes the oil market. For simplicity, the low-cost non-OPEC oil producer has the same cost than OPEC, $c_L^O = c_i^O$, where $c_i^O \in (0,1)$. We consider that OPEC's capacity is Q_i^O and that for the non-OPEC producers is K_j^O where $K_j^O \neq Q_i^O$ for all $j = H, L$.

OPEC can choose between two strategies: squeeze or accommodate. If OPEC decides to squeeze, it increases production such that the price is lower than c_H^O driving high cost producers out of the market. However, if it accommodates, the price is equal to c_H^O such that high cost producers find it profitable to produce at zero profits in the oil market. The global demand for oil takes the linear form

$$P^O = (\alpha - \gamma Q_L^R - \beta Q^O)$$
$$P^R = (\alpha - \gamma Q^O - \beta Q_L^R)$$

where α, β, γ are parameters and α, $\beta > 0$. In addition, γ represents the degree of product differentiation, which ranges from zero (completely differentiated goods) to β (homogeneous goods) and $\beta^2 > \gamma^2$ implying that the own-price effect dominates the cross-price effect. The price of oil and renewable energy are P^O and P^R, respectively. The aggregate quantity for renewable energy is Q_L^R and the marginal cost of production is c_L^R, which is strictly positive. The aggregate quantity for oil is defined as $Q^O = Q_i^O + K_H^O + K_L^O$, that is, the sum of oil produced by OPEC, high-cost and low-cost non-OPEC producers. We consider that the renewable energy market is in its initial stage and, thus, the low-cost non-OPEC producer enjoys monopoly power.

Summarizing, OPEC first decides whether to accommodate or squeeze and, the low-cost non-OPEC producer, after observing OPEC's strategy, decides its output level in both oil and renewable energy markets. We next examine the second stage of the game separately considering OPEC's strategies, i.e., accommodate or squeeze.

2.1.1 Accommodate

Let us focus on a representative low-cost non-OPEC producer, which operates in both markets (oil and the renewable sector).[9] Let superscript A denote OPEC's accommodate strategy. The low-cost non-OPEC's maximization problem is

$$\max_{Q_L^R} \pi_L^A = K_L^O\{(\alpha - \gamma Q_L^R - \beta Q^O) - c_L^O\} + Q_L^R\{(\alpha - \gamma Q^O - \beta Q_L^R) - c_L^R\},$$

where the first (second) term represents net profits from the oil market (renewable market, respectively). Substituting $Q^O = Q_i^0 + K_H^O + K_L^O$ and $c_L^O = c_i^O$ we can rewrite the low-cost non-OPEC's maximization problem as follows

$$\max_{Q_L^R} \pi_L^A = K_L^O\{\alpha - \gamma Q_L^R - \beta\left(Q_i^0 + K_H^O + K_L^O\right) - c_i^O\} + Q_L^R\{\alpha - \gamma\left(Q_i^0 + K_H^O + K_L^O\right) - \beta Q_L^R - c_L^R\}$$

and taking first order condition with respect to Q_L^R we obtain the low-cost non-OPEC's best response function,

$$Q_L^R\left(Q_i^0\right) = \frac{\alpha - \gamma\left(K_H^O + 2K_L^O\right) - c_L^R}{2\beta} - \frac{\gamma Q_i^0}{2\beta}. \tag{1}$$

If γ approaches to β, oil and renewables become homogeneous products and the best response function is more responsive to changes in the output level of the other good. However, when γ approaches to zero, both goods are completely differentiated and, consequently, the output level of renewable energy does not depend on oil production by OPEC. Conditional on accommodating, the maximization problem for OPEC in the first period is

$$\max_{Q_i^O} \pi_i^A = Q_i^O\{\left(\alpha - \gamma Q_L^R\left(Q_i^0\right) - \beta Q^O\right) - c_i^O\}.$$

where $Q_L^R\left(Q_i^0\right)$ comes from equation (1). Solving for production of oil yields

$$Q_i^{O*} = \frac{\alpha(2\beta - \gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) - 2\beta c_i^0}{4\beta^2 - 2\gamma^2}. \tag{2}$$

Plugging Q_i^{O*} back into the equation (1) we obtain the optimal renewable output

[9] Recall that high-cost non-OPEC producers always operate up to their maximum capacity. They cannot influence oil prices and do not produce renewable energy. Hence, we here focus our analysis on the low-cost non-OPEC producer.

$$Q_L^{R*} = \frac{\alpha(4\beta^2 - 2\beta\gamma - \gamma^2) + 2\beta\gamma c_i^0 - 2\beta^2(2c_L^R + \gamma K_H^O + 3\gamma K_L^O) + \gamma^2(2c_L^R + \gamma K_H^O + 3\gamma K_L^O)}{8\beta^3 - 4\beta\gamma^2}. \quad (3)$$

Therefore, considering (2) and (3) we can identify optimal prices in both sectors,

$$P^{O*} = \frac{\alpha(2\beta - \gamma) + 2\beta c_i^0 - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O)}{4\beta}, \quad (4)$$

$$P^{R*} = \frac{\alpha(4\beta^2 - 2\beta\gamma - \gamma^2) + 2\beta\gamma c_i^0 + 2\beta^2(2c_L^R - \gamma K_H^O + \gamma K_L^O) + \gamma^2(\gamma K_H^O - 3c_L^R - 2\gamma K_L^O)}{8\beta^2 - 4\gamma^2}. \quad (5)$$

We consider that the high-cost non-OPEC producer can stay in the market if OPEC decides to accommodate. This can be guaranteed if the cost differential between an inefficient non-OPEC and OPEC producers is not sufficiently high. Therefore, it must be that for accommodate to be viable $P^{O*} \geq c_H^O$. Using equation (4) we obtain

$$\alpha(2\beta - \gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma^2(K_H^O + 2K_L^O) + \gamma c_L^R \geq 2\beta(2c_H^O - c_i^0) \quad \text{(condition 1)}$$

If this condition holds then the price of oil set by OPEC is high enough for an inefficient oil producer to stay in the market. Also, for oil prices to be more competitive relative to renewable energy, it must be that the price of oil is lower than that of renewables when OPEC decides to accommodate, i.e., $P^{O*} < P^{R*}$. For this to hold we compare equations (4) and (5) and solve for c_i^0, which yields

$$c_i^0 < \frac{2\beta\gamma(c_L^R - \gamma K_H^O) + 2\beta^2\left(2c_L^R + \gamma\left(K_H^O + 3K_L^O\right)\right) + 4\beta^3(K_H^O + K_L^O) - \gamma^2(c_L^R + \gamma K_H^O + 2\gamma K_L^O - \alpha)}{2\beta(2\beta + \gamma)} \equiv \bar{c}_i^O. \quad (6)$$

That is, the price of oil is lower than the price of renewable energy if the cost of producing oil is sufficiently low. This ensures that even if oil and renewable energy are homogeneous, oil represents a more competitive market when OPEC chooses the accommodate strategy.[10] We next examine OPEC's profit under the accommodate strategy. All proofs are relegated to the appendix.

Lemma 1. *If OPEC decides to accommodate profits are,*

$$\pi_i^{A*} = \frac{(\alpha(2\beta - \gamma) - 2\beta c_i^0 - 2\beta^2(K_H^O + K_L^O) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O))^2}{16\beta - 8\beta\gamma},$$

which decreases in γ *if* $c_L^R \in [X, Y]$, *and* $c_i^0 \leq \hat{c}_i^0$, *where* $X \equiv \frac{\alpha(\gamma - 2\beta) + 2\beta c_i^0 + 2\beta^2\left(K_H^O + 2K_L^O\right) - \gamma^2\left(K_H^O + 2K_L^O\right)}{\gamma}$,

$Y \equiv \frac{2\alpha\beta(\beta - \gamma) + \gamma\left(2\beta c_i^0 - 2\beta^2\left(K_H^O + 3K_L^O\right) + \gamma^2\left(K_H^O + 2K_L^O\right)\right)}{2\beta^2}$, *and* $\hat{c}_i^0 \equiv \frac{2\alpha\beta - 2\beta^2\left(K_H^O + K_L^O\right) - \gamma^2(K_H^O + 2K_L^O))}{2\beta}$.

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[10] If the cost of oil is not sufficiently low, renewable energy could replace oil when they are considered homogenous.

If the cost of producing renewables is intermediate, the oil production cost is low, and both goods are perceived as homogeneous, the accommodate strategy becomes less profitable for OPEC. In this context, the low-cost non-OPEC producer has the capacity to capture a higher market share since goods are perceived as homogeneous (business stealing effect), negatively affecting OPEC's profit from accommodate. We next examine OPEC's squeeze strategy.

2.1.2 Squeeze

If OPEC decides to squeeze, it must set a price lower than the cost of the inefficient oil producers, $P^0 = c_H^O - \varepsilon$, where $\varepsilon > 0$ is the markdown of the oil price from the least efficient oil producers' marginal cost. Consequently, for $\gamma \neq 0$, the global demand curve can be re-written as follows,

$$Q^O = \left(\alpha - \gamma Q_L^R - c_H^O + \varepsilon\right)/\beta.$$

Given that the total oil production capacity under squeeze is $Q^O = Q_i^0 + K_L^O$, then

$$Q_i^0 = \frac{\left(\alpha - \gamma Q_L^R - c_H^O + \varepsilon\right)}{\beta} - K_L^O. \tag{7}$$

Using equation (1) and considering that $K_H^O = 0$ and solving for Q_i^{O*} we obtain

$$Q_i^{0*} = \frac{2\beta\left(\alpha + \varepsilon - c_H^O\right) - \gamma(\alpha - c_L^R) - 2K_L^O(\beta^2 - \gamma^2)}{2\beta^2 - \gamma^2}\ . \tag{8}$$

Plugging Q_i^{0*}into equation (1) to get optimal Q_L^{R*} we have that

$$Q_L^{\mathrm{R}*} = \frac{\alpha(\beta - \gamma) - \beta\left(c_L^R + \gamma K_L^O\right) + \gamma(c_H^O - \varepsilon)}{2\beta^2 - \gamma^2}\ . \tag{9}$$

Considering Q_L^{R*} and Q_i^{0*} into demand function, we obtain optimal prices

$$P^{R*} = \frac{\alpha\beta(\beta - \gamma) + \beta^2(c_L^R + \gamma K_L^O) - \gamma^2(c_L^R + \gamma K_L^O) + \beta\gamma(c_H^O - \varepsilon)}{2\beta^2 - \gamma^2} \tag{10}$$

$$P^{o*} = c_H^O - \varepsilon\ . \tag{11}$$

Comparing equations (10) and (11), $P^{R*} > P^{o*}$ is satisfied when,

$$c_H^O < \frac{\alpha\beta + \gamma(c_H^O + \varepsilon + \gamma K_L^O) + \beta(c_H^O + 2\varepsilon + \gamma K_L^O)}{2\beta + \gamma}\ . \tag{12}$$

The price of renewable energy is greater than oil in the squeeze strategy when the cost of the high cost producer is sufficiently low. In other words, a small cost differential between high and low-cost producers induces OPEC to set a lower price (relative to renewable price) to keep the high-cost non-OPEC producer out of the market. We next examine OPEC's profits when it decides to squeeze.

Lemma 2. *If OPEC decides to squeeze its profits are,*

$$\pi_i^{S*} = \frac{(\alpha(\gamma - 2\beta) - 2\beta(\varepsilon - c_H^O) + 2\beta^2 K_L^O - \gamma(c_L^R + 2\gamma K_L^O))(c_i^0 + \varepsilon - c_H^O)}{2\beta^2 - \gamma^2},$$

which increases in γ *if* $c_L^R \geqslant \frac{\alpha(2\beta^2 - 4\beta\gamma + \gamma^2) - 4\beta\gamma(\varepsilon + \beta K_L^O - c_H^O)}{2\beta^2 + \gamma^2}$.

The squeeze strategy is more profitable when both goods become more homogeneous and the cost of producing renewable energy is relatively high. A high production cost for the renewable good makes the low-cost non-OPEC producer less competitive. Hence, it can capture a lower share of the oil market (since oil and renewable energy are perceived as homogeneous), thus, making the squeeze strategy more attractive. That is, the business stealing effects are not sufficiently strong increasing the benefits from the squeeze strategy for OPEC. In order to examine the OPEC's optimal strategy, we next identify the profit change denoted as

$$\Delta \pi_i = \pi_i^{S*} - \pi_i^{A*},$$

which represents the difference between profits when OPEC squeezes and accommodate. Hence, if this difference is positive, the squeeze strategy provides a higher benefit. The following proposition discusses our findings.

Proposition 1. *OPEC finds the squeeze strategy more profitable* ($\Delta \pi_i > 0$) *than accommodate if* K_H^O *and* c_L^R *are sufficiently high. In addition,* $\Delta \pi_i$ *increases when:*

- *i.* *Renewable energy and oil become less differentiated,* $\gamma \to \beta$, *and* c_L^R *is sufficiently high.*
- *ii.* *Production capacity for high cost non-OPEC producers* (K_H^O) *increases.*
- *iii.* *Marginal cost of oil for high cost producers* (c_H^0) *increases.*

When oil and renewable energy become more homogenous, OPEC's profits decrease independent of the strategy it chooses. However, profits from accommodate decrease more significantly than those from squeezing.[11] If both products become more homogeneous and the cost differential is high, a more aggressive strategy (squeeze) helps OPEC eliminate competition and ensure higher profits. In addition, as the production capacity of high-cost non-OPEC producers

[11] If both goods are perceived as homogenous, profits from accommodate are positive if $\beta < 2$, see proof of proposition 1. While profits from squeeze are positive when the cost of renewable energy is sufficiently high.

increases, it becomes more attractive to squeeze since it guarantees that producers that could capture a larger share of the market are driven away. Similarly, if the marginal cost of high-cost non-OPEC producers increases, the squeeze strategy is easier to implement. Specifically, the increase in production required to reach a price that keeps inefficient producers out of the industry is less demanding. We next compare the low-cost non-OPEC's production levels of renewable energy in the squeeze strategy with that in the accommodate strategy.

Lemma 3. *The low-cost non-OPEC's production of renewable energy under the squeeze strategy is higher than under accommodate when* $c_L^R < \tilde{c}$ *and both goods are relatively homogeneous. In addition, production of renewable energy increases as:*

i. *The global demand of crude oil* (α) *decreases.*
ii. *Oil production capacity for low-cost non-OPEC producers* (K_L^O) *decreases and* $\gamma > \sqrt{2}$.
iii. *Marginal cost of renewable energy* (c_L^R) *decreases.*

where, $\tilde{c} = \frac{\alpha(\gamma-2\beta)-2\beta(c_i^0+2\varepsilon-2c_H^0)+2\beta^2(K_H^O+K_L^O)-\gamma^2(K_H^O+2K_L^O)}{\gamma}$.

When marginal cost of renewable energy is sufficiently low and oil and renewable energy become more homogeneous, the low-cost non-OPEC producer can compete more effectively and, therefore, produce relatively more in the squeeze strategy. That is, when OPEC chooses squeeze, OPEC's production increases, which entails more incentives for the non-OPEC to increase renewables production when both goods are substitutable in consumption. A decrease in global demand for oil also induces the efficient OPEC's competitor to produce more renewable energy, especially when the squeeze strategy is in place. Similarly, it will produce more renewable energy when its production capacity of oil decreases. Given that both goods are perceived as sufficiently homogeneous, $\gamma > \sqrt{2}$, the low-cost non-OPEC can make up from the loss of profits in the oil market increasing its production of renewable energy. Lastly, as production cost of renewable energy decreases, it is cheaper to produce it and, therefore, production increases.

3. The low-cos non-OPEC influences price

In this model the non-OPEC producer can also choose between squeeze or accommodate. Similar than our previous analysis, we consider that it produces renewable energy. However, we now assume that it can influence price. In addition, the model setup is similar to our benchmark case, where OPEC is the Stackelberg leader. That is, after observing the OPEC's strategy, the low-cost non-OPEC responds with squeeze or accommodate. Finally, in order to facilitate the exposition of our result we hereafter assume that $\alpha, \beta = 1$.

3.1.1 Non-OPEC and OPEC Accommodate

We start operating by backward induction and first analyze non-OPEC's strategy. We consider the case in which OPEC accommodates. Specifically, we analyze under which conditions a low-cost non-OPEC producer also decides to accommodate. In this case, it chooses an output level for oil and renewable energy that maximizes its profits as follows,

$$\max_{Q_L^R, K_L^O} \pi_L^{A,A} = K_L^O\{1 - \gamma Q_L^R - (Q_i^0 + K_H^O + K_L^O) - c_i^O\} + Q_L^R\{1 - \gamma\left(Q_i^0 + K_H^O + K_L^O\right) - Q_L^R - c_L^R\}.$$

Taking first order condition with respect to K_L^O and Q_L^R and solving we obtain

$$K_{\mathrm{L}}^O(Q_i^O) = \frac{(1-\gamma) - C_i^0 - (K_H^O + Q_i^0) + \gamma(c_H^O + \gamma(K_H^O + Q_i^0))}{2(1-\gamma^2)} \tag{13}$$

$$Q_L^{R*} = \frac{1 - c_L^R - \gamma(1 - c_i^0)}{2(1-\gamma^2)}\,. \tag{14}$$

We next examine OPEC's output decision when it accommodates,

$$\max_{Q_i^O} \pi_i^{A,A} = Q_i^O\{1 - \gamma Q_L^R - (Q_i^0 + K_H^O + K_{\mathrm{L}}^O(Q_i^O)) - c_i^O\}$$

Substituting the best response functions of non-OPEC, as stated in equations (13) and (14), into the optimization problem of OPEC and solving for optimal production of oil, yields

$$Q_{\mathrm{i}}^{O*} = \frac{1 - c_i^O - K_H^O}{2}\,. \tag{15}$$

Plugging equation (15) into equations (13) and (14), we find

$$K_{\mathrm{L}}^{O*} = \frac{(1-\gamma)^2 + \gamma(2c_L^R + \gamma K_H^O) - c_i^O - c_i^O\gamma^2 - K_H^O}{4(1-\gamma^2)}. \tag{16}$$

Substituting $K_{\mathrm{L}}^{O*}, Q_{\mathrm{i}}^{O*}$ and Q_L^{R*} into the demand function we obtain

$$P^{O*} = \frac{1}{4}\left(1 + 3c_i^0 - K_H^O\right) \tag{17}$$

$$P^{R*} = \frac{2(1 + c_L^R) - \gamma(1 - c_i^0) - \gamma K_H^O}{4}\,. \tag{18}$$

The price of the renewable energy decreases if both goods become more homogeneous. We next examine the low-cost non-OPEC's profits for the case in which it decides to accommodate, given that OPEC also accommodates.

Lemma 4. *The low-cost non-OPEC's profits from accommodate given that OPEC accommodates, are*

$$\pi_L^{A,A*} = \frac{\left({c_i^0}^2 + 4{c_L^R}^2 - \gamma^2 {K_H^O}^2\right) + \Gamma - 2c_i^0\gamma\eta - 2(1-\gamma)\left(K_H^O - 3c_i^0\gamma + \left(c_i^0 + \eta\right)\right)}{16(1-\gamma^2)},$$

where $\eta = 4c_L^R + \gamma K_H^O$ *and* $\Gamma = 3{c_i^0}^2\gamma^2 + (5 - 8\gamma + 3\gamma^2) + 2c_i^0 K_H^O + {K_H^O}^2$. *In addition, these profits increase if: marginal cost of renewable energy* (c_L^R) *decreases if and only if products are sufficiently differentiated, i.e.,* $\gamma < \frac{1-c_L^R}{1-c_i^0}$.

If renewable energy and oil are sufficiently differentiated, lower marginal cost of renewable energy leads to higher profits for low-cost non-OPEC producers as they can secure higher benefits in the renewable market.

3.1.2 Non-OPEC Accommodates but OPEC squeezes

Now we analyze the case where OPEC squeezes while low-cost non-OPEC accommodates. First, the low-cost non-OPEC producer maximizes profits as follows:

$$\max_{Q_L^R, K_L^O} \pi_L^{A,S} = K_L^O\{1 - \gamma Q_L^R - (Q_i^0 + K_H^O + K_L^O) - c_i^O\} + Q_L^R\{1 - \gamma\left(Q_i^0 + K_H^O + K_L^O\right) - Q_L^R - c_L^R\}$$

$$\text{subject to } K_H^O = 0$$

$$P_i^{O*} = c_H^O - \varepsilon.$$

Taking first order condition with respect to Q_L^R and K_L^O and solving we obtain

$$K_{\mathrm{L}}^O(Q_i^0) = \frac{(1-\gamma) - c_i^0 - Q_i^0 + \gamma(c_L^R + \gamma Q_i^0)}{2(1-\gamma^2)} \quad (19)$$

$$Q_L^{R*} = \frac{1 - c_L^R - \gamma + c_i^0\gamma}{2(1-\gamma^2)}. \quad (20)$$

We next examine OPEC's output decision when it squeezes. OPEC sets a price lower than the cost of the inefficient oil producers where $K_H^O = 0$. Since OPEC charges $P_i^{O*} = c_H^O - \varepsilon$, we have that

$$Q_i^0 = \left(1 - \gamma Q_L^R - c_H^O + \varepsilon\right) - K_{\mathrm{L}}^O(Q_i^0). \quad (21)$$

Plugging in equations (19) and (20) into equation (21) we obtain,

$$Q_i^{O*} = 1 + c_i^O + 2\varepsilon - 2c_H^O\,. \quad (22)$$

Considering Q_i^{O*}into equation (19) we find,

$$K_L^{O*} = \frac{\gamma(c_L^R - 1) + \gamma^2(1 + c_i^0 + 2\varepsilon - 2c_H^O) - 2(c_i^0 + \varepsilon - c_H^O)}{2(1-\gamma^2)}. \quad (23)$$

Finally, plugging (20), (22) and (23) into demand function we obtain the optimal price of oil and renewable energy set by the low-cost non-OPEC,

$$P_L^{O*} = c_H^O - \varepsilon \,,$$

$$P_L^{R*} = \frac{c_L^R + (1-\gamma) - \gamma\left(c_i^0 + 2\varepsilon - 2c_H^O\right)}{2}\,.$$

Hence, in the case in which the OPEC decides to squeeze, the low-cost non-OPEC also chooses the same price strategy. This finding indicates that the low-cost non-OPEC deviates from the accommodate strategy, thus, making it impossible to arise.

3.1.3 Non-OPEC squeezes and OPEC accommodates

Next, we analyze under which conditions the low-cost non-OPEC producer decides to squeeze when OPEC chooses to accommodate. In this context the low-cost non-OPEC producer sets a price equal to $P_L^{O*} = c_H^O - \varepsilon$, and produces oil corresponding to its maximum production capacity, that is,

$$K_L^{O*} = \overline{K}_L^O.$$

In the case of renewable energy production, the low-cost non-OPEC producer chooses an output that solves

$$\max_{Q_L^R} \pi_L^{S,A} = \overline{K}_L^O\{(c_H^O - \varepsilon) - c_i^O\} + Q_L^R\{1 - \gamma\left(Q_i^0 + \overline{K}_L^O\right) - Q_L^R - c_L^R\}$$

Taking first order condition with respect to Q_L^R we obtain

$$Q_L^R(Q_i^O) = \frac{1 - c_L^R - \gamma\left(\overline{K}_L^O + Q_i^O\right)}{2}\,. \tag{24}$$

Here we consider that OPEC accommodates. Plugging $\overline{K}_L^O$ and Q_L^R from equation (24) into the maximization problem of OPEC and solving for Q_i^O we obtain

$$Q_i^{O*} = \frac{(2-\gamma) - 2c_i^0 - 2\overline{K}_L^O + \gamma\left(c_L^R + \gamma\,\overline{K}_L^O\right)}{2-\gamma^2}\,. \tag{25}$$

Plugging Q_i^{O*} into equation (24) we have that

$$Q_L^{R*} = \frac{\gamma c_i^0 - c_L^R + (1-\gamma)}{2-\gamma^2}\,. \tag{26}$$

Considering equations (26) and (25) and $\overline{K}_L^O$ into the demand function and solving for the optimal prices

$$P_i^{O*} = c_i^0 \tag{27}$$

$$P_L^{R*} = c_L^R + \frac{((1-\gamma) - c_L^R + \gamma c_i^0)}{2-\gamma^2} \tag{28}$$

Because OPEC accommodates it must be that $P_i^{O*} \geq c_H^O$, which is not satisfied since $c_H^O > c_i^0$. Hence, similar than the previous case, when the low-cost non-OPEC chooses to squeeze OPEC follows the same strategy.

3.1.4 Non-OPEC and OPEC squeeze

If OPEC decides to squeeze, we now plug $\overline{K}_L^O$ and equation (24) into equation (21) where OPEC sets price $P_i^{O*} = c_H^O - \varepsilon$ and $K_H^{O*} = 0$, we obtain

$$Q_i^{0*} = \frac{2(1+\varepsilon) - \gamma(1-c_L^R) - 2(\overline{K}_L^O + 2c_H^0) + \gamma^2 \overline{K}_L^O}{2-\gamma^2} \ . \tag{29}$$

Plugging equation (29) into equation (24) we obtain the optimal production of renewable energy

$$Q_L^{R*} = \frac{1 - c_L^R - \gamma(1+\varepsilon) + \gamma c_H^0}{2-\gamma^2} \ . \tag{30}$$

Therefore, optimal prices in the two sectors are,

$$P^{O*} = c_H^O - \varepsilon \tag{31}$$

$$P_L^{R*} = \frac{c_L^R + (1-\gamma) - c_L^R\gamma^2 + \gamma(c_H^0 - \varepsilon)}{2-\gamma^2}. \tag{32}$$

If both goods are perceived as completely homogeneous, $\gamma = 1$, the non-OPEC producer sets a price for the renewable good similar to the oil price. However, if goods are completely differentiated, $\gamma = 0$, the price strategy is different. In this case, the price of the renewable good is higher than oil if the cost of producing renewables is sufficiently high, i.e., $c_L^R > 2(c_H^O - \varepsilon) - 1$. We next examine low-cost non-OPEC's profits when both firms squeeze. In this case, the low-cost non-OPEC produces oil up to its maximum capacity.

Lemma 5. *The low-cost non-OPEC's profits from squeeze given that OPEC squeezes are*

$$\pi_L^{S,S*} = \frac{(c_L^R - (1-\gamma) + \gamma(\varepsilon - c_H^O))^2}{(2-\gamma^2)^2} - \overline{K}_L^O (c_i^0 + \varepsilon - c_H^O).$$

In addition, these profits increase when renewable energy and oil become less differentiated if $c_L^R > \frac{(2+\gamma^2)(c_H^O - \varepsilon) - (2 - 2\gamma + \gamma^2)}{2\gamma}$.

A relatively high cost of producing renewables makes the efficient non-OPEC producer to obtain a lower profit in the less competitive renewable market. In this context, the squeeze strategy induces the high-cost non-OPEC to stay out of the oil market, implying a larger market share for the low-cost non-OPEC producer. If oil and renewables are perceived as homogeneous and the cost of renewables is high, then the squeeze strategy is always preferred since it generates higher profits. However, if the low-cost non-OPEC becomes also more efficient producing renewables, becoming more homogeneous will induce it to choose the accommodate strategy.

3.2. OPEC's optimal strategy

We now examine the optimal strategy of OPEC. We first study OPEC's strategy considering that the non-OPEC producer decides to accommodate. In this case the optimal profit of OPEC is

$$\pi_i^{A,A*} = \frac{(1 - c_i^O - K_H^O)^2}{8}$$

From our previous findings, the low-cost non-OPEC always squeezes when OPEC squeezes for all parameter values. Hence, the outcome of OPEC squeezing when low-cost non-OPEC accommodates ($\pi_i^{S,A*}$) is not feasible. A similar argument applies for the case where low-cost non-OPEC squeeze and OPEC accommodates. Therefore, from our previous results we can derive OPEC's optimal profit when non-OPEC squeezes, which are

$$\pi_i^{S,S*} = \frac{(2\overline{K}_L^O - (1-\gamma) - \gamma(c_L^R + \gamma\overline{K}_L^O) - 2(\varepsilon - c_H^O))(c_i^0 + \varepsilon - c_H^O)}{2-\gamma^2}.$$

Let us next identify the difference in profits for OPEC when it chooses to squeeze and to accommodate.

$$\Delta\,\pi_i = \pi_i^{\mathrm{S,S}*} - \pi_i^{\mathrm{A,A}*}.$$

This difference focuses on the two feasible strategies previously identified, in which both players choose the same action. Hence, if this difference is positive, OPEC receives higher profits squeezing (which is responded with squeeze) than accommodating. The following proposition discusses our findings.

Proposition 2. *OPEC finds the squeeze strategy more profitable* $(\Delta\, \pi_i > 0)$ *than accommodate if* $c_L^R < \Psi$, *where* $\Psi \equiv \frac{(2-\gamma^2)(8\left(c_i^0+\varepsilon-c_H^O\right)\left[2\left(\varepsilon-c_H^O\right)-2\overline{K}_L^O+(2-\gamma)+\overline{K}_L^O\gamma^{2}\right]+(2-\gamma^2)\left(-1+c_i^O+K_H^O\right)^2)}{8\gamma(c_H^O-c_i^0-\varepsilon)(2-\gamma^2)}$.

Hence, a low-cost non-OPEC producer being relatively efficient in producing renewable energy will choose to squeeze inducing OPEC to select squeeze as well. As a consequence, renewables that are recently discovered (early stage of the technology and, hence, costs are intermediate or high) are less likely to trigger an aggressive strategy from OPEC.

4. Without any production of renewable energy

We now consider the case in which the low-cost non-OPEC producer is not price taker but assume that it does not produce renewable energy. The low-cost non-OPEC, therefore, only maximizes profits in the oil market.

Proposition 3. *The low-cost non-OPEC is more likely to squeeze when production of renewable energy is allowed.*

When the low-cost non-OPEC does not produce renewable energy, the OPEC does not face a potential business-stealing effect from this product. This effect is larger when products are more homogeneous but does not exist when products are highly differentiated. Therefore, when the low-cost non-OPEC firm does not produce renewables (or it does, but it is completely differentiated with oil products), the OPEC faces a lower threat and, thus, is less likely to squeeze. In contrast, when the low cost non-OPEC firm produces renewable energy, and such product is regarded as relatively homogeneous to oil, OPEC faces a serious threat from non-OPEC, leading OPEC to squeeze under larger parameter conditions.

5.Discussion

In 2008 the price of crude oil was around $150 a barrel. Since then most of the oil production came from OPEC, they were able to influence the price of oil by either cutting back or boosting production. This is depicted by our first model where OPEC is a Stackelberg leader and other oil producers are price takers. In 2009, President Obama called for doubling renewable energy within the following three years which brought about "a new era of energy exploration" in the United States.[12] High oil prices were sustained by coordinated production cuts by OPEC until mid-2014.

In 2014 there was a surge in American crude oil which led to a global glut in oil. The excess supply caused oil prices to peak in mid-2014 and crash from $100 per barrel to less than $50.[13] This was because supply exceeded the demand for oil during that time. Since then OPEC has been boosting oil production in order to keep prices low and drive the US shale out of the market. US shale was still considered a high cost producer and therefore, OPEC aimed to lower price enough to be able to force the higher cost US shale oil producers out of the market.[14] Our results indicate that as production capacity of high-cost non-OPEC producers increase (namely inefficient US shale oil producers), it becomes more attractive to choose squeeze since it guarantees that inefficient producers are driven away, allowing OPEC to capture a bigger portion of the market share.

By 2016, for certain US oil company's production costs had almost halved since 2014 and they started pumping crude at a price almost as low as that enjoyed by OPEC giants Iran and Iraq.[15] This was due to improved technology and drilling techniques which boosted efficiency for the US oil industry. The shale oil revolution made US one of the leading producers, surpassing Saudi Arabia and Russia even during low oil prices.[16] Hence, the US was not considered a high cost producing country anymore either but had shifted to an efficient low-cost oil producing country. This implies that OPEC were not the only ones that could influence price and the US shale were not price takers anymore. By now, renewable energy in the US also accounted for 12.2 percent of total primary energy consumption and wind power at 5.55 percent of total power production until 2016.[17] Hydroelectric power was the largest producer of renewable electricity in the country, generating around 6.5 percent of the nation's total electricity followed by wind power and solar

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[12] For more details see: https://web.archive.org/web/20090429191826/http://apps1.eere.energy.gov/news/news_detail.cfm/news_id percent3D12475

[13] For more details see: https://www.vox.com/2014/12/16/7401705/oil-prices-falling

[14] Saudi Arabia signaled an output free-for-all in order to drive higher-cost shale producers out of the market. However, instead of driving the US shale industry, the ensuing two-year price war made shale a stronger rival, even in the current low-price environment. For more details see: https://www.cnbc.com/2016/11/30/leaner-and-meaner-us-shale-greater-threat-to-opec-after-oil-price-war.html

[15] For more details see: https://www.cnbc.com/2016/11/30/leaner-and-meaner-us-shale-greater-threat-to-opec-after-oil-price-war.html

[16] For more details see: https://www.cnn.com/2019/06/10/business/oil-boom-production-opec/index.html

[17]For more details see: https://www.eia.gov/totalenergy/data/monthly/pdf/sec1_5.pdf

energy. In 2017, while OPEC still produced 42.6 percent of the world's oil, majority of new oil production came from the US.[18] In the same year OPEC sent a plea to the US to stop pumping so much oil. This corresponds to our second setting, where OPEC would find it more profitable to accommodate only when low-cost non-OPEC is also accommodating. By 2018, US was exporting higher than the individual country exports of 12 out of 14 OPEC members.[19] According to the Energy Information Administration, in 2018 US production of oil was 10 million barrels per day making US and Saudi Arabia the largest oil producing countries.[20] In case of renewable energy as well, the United States solar power generation increased by 24.4 percent in 2017 and 53.2 percent over the decade. Power from geothermal and biomass grew at an annual average of 7.1 percent. US remains second in place in renewable energy globally after China with a 16.6 percent share according to the Statistical Review of World Energy 2019. Our second model explains why US shale is more likely to squeeze when OPEC squeezes especially as renewable energy and oil become less differentiated and cost of renewable energy is lower. They can produce more renewable energy and compete in the oil market, capturing a larger proportion of the market share. Currently, in 2020 the oil prices have been falling rapidly and is facing lowest price since the financial crisis.

Differentiation, oil vs. renewables. As of now, there is no renewable energy that is a perfect substitute or perceived completely homogenous to oil and gas. Fossil fuels offer the benefit of being a reliable resource that has near-constant availability. For the case of airplanes, no alternative for oil for internal combustion engines is found. Also, plastic production relies on oil-based petrochemicals and cannot be produced by renewable energy. The ultimate way to compare renewable energy to fossil fuels, in order to find if they are considered relatively homogenous is by cost. According to the Renewable Power Generation Costs report,[21] the global average cost of

[18] The high levels of US oil production surge broke OPEC's monopoly power on global oil prices. For more details see: https://www.forbes.com/sites/rrapier/2018/07/22/how-the-fracking-revolution-broke-opecs-hold-on-oil-prices/#3c81220e48ef

[19] Exports were also higher than the crude oil production of all but three OPEC members—Saudi Arabia, Iraq, and Iran. For more details see: https://www.businessinsider.com/us-pumping-out-more-oil-than-12-of-14-opec-members-2018-7

[20] Although OPEC produces more oil than the US on a daily basis, the United States is the top producing nation. As oil prices rise, US oil companies pump out more oil to capture higher profits. The result limits OPEC's ability to influence the price of oil. Historically, OPEC's production cuts had devastating effects on global economies. Although still influential, OPEC's influence on prices has diminished with the US now a top oil producer. For more details see: https://www.investopedia.com/articles/investing/081315/opec-vs-us-who-controls-oil-prices.asp

[21] For more details see: https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018, https://www.forbes.com/sites/dominicdudley/2019/05/29/renewable-energy-costs-tumble/#2b111ad8e8ce

renewable energy has dropped even further in 2018, to the point where most renewable energy can now compete on cost with oil, coal and gas-fired power plants. According to the report, hydroelectric power is the cheapest source of renewable energy, at an average of $0.05 per kilowatt hour (kWh). The average cost of developing new power plants based on onshore wind, solar photovoltaic (PV), biomass or geothermal energy is now typically below $0.10/kWh while offshore wind costs around $0.13/kWh. Also, solar energy's low-cost trajectory is likely to continue. Which implies that all these renewable energies are now able to compete with the cost of developing new power plants based on oil and gas, which typically range from $0.05/kWh to over $0.15/kWh. In this setting our model reports that the squeeze strategy is more likely to arise since the cost of the renewable energy is sufficiently low. This might explain why Saudi is thinking of making a big investment in solar energy. [22] This will give them market power in both the oil and renewable market.

6. Conclusion

We examine a game where OPEC decides between two strategies, squeeze or accommodate, and the efficient non-OPEC also produces renewables energy. We follow a similar approach than Behar and Ritz (2017) but we allow for the production of renewables. In addition, we also consider the case in which the efficient non-OPEC can influence prices. We find that relative to the case in which there is no production of renewables, the squeeze strategy arises under larger conditions when the low-cost non-OPEC also operates in the market for renewables. In addition, we show that the squeeze strategy is more likely to arise if oil and renewables are perceived as homogeneous and the cost of renewables is relatively low.

Our model considers that the low-cost non-OPEC producer has monopoly power on the renewable market. Hence, a different market structure for the renewable good could be a potential extension of our model. In this case, the low-cost non-OPEC will not be able to compensate the losses from a tough competitor. Hence, we expect the OPEC's strategic behavior to be different in this context. It would be interesting to analyze the case in which OPEC also produces renewable energy, which could affect our equilibrium results. Finally, another extension could be a context in which OPEC is not able to observe the cost of producing renewables. In this setting, OPEC does

[22] For more details see: https://oxfordbusinessgroup.com/news/plan-turn-saudi-arabia-renewable-energy-leader

not know if it faces an efficient or inefficient non-OPEC producer, which could affect its strategic actions.

References

Almoguera, P.A., Douglas, C.C. and Herrera A.M. (2011). Testing for the cartel in OPEC: non-cooperative collusion or just non-cooperative? *Oxford Review of Economic Policy*, 27, 144-168.

Ansari, D. (2017). OPEC, Saudi Arabia, and the shale revolution: Insights from equilibrium modelling and oil politics. *Energy Policy*, 111, 166-178.

Behar, A. and Ritz, R. (2017). OPEC vs US shale: Analyzing the shift to a market-share strategy. *Energy Economics*, 63, 185-198.

Brown, S.P.A. and Huntington H.G. (2017). OPEC and world oil security, *Energy Policy*, 108, 512-523.

Colgan J.D. (2014). The emperor has no clothes: the limits of OPEC in the global oil market. *International Organization*, 68(3), 599-632.

Fattouh B. and Mahadeva, L. (2013). OPEC: what difference has it made? *Annual Review Resource Economics*, 5, 427-443.

Fattouh, B., Poudineh, R. and Sen, A. (2016). The dynamics of the revenue maximization–market share trade-off: Saudi Arabia's oil policy in the 2014–15 price fall. *Oxford Review of Economic Policy*, 32(2), 223-240.

Gately, D. (1989). Do oil markets work? is OPEC dead? *Annual Revenue Energy*, 14, 95-116.

Genc, T. (2017). OPEC and demand response to crude oil prices. *Energy Economics*, 66, 238.

Huppmann, D. (2013). Endogenous Shifts in OPEC Market Power: A Stackelberg Oligopoly with Fringe. *Working Paper at DIW Berlin*, 1313.

Huppmann, D. and Holz, F. (2012). Crude Oil Market Power-A Shift in Recent Years? *The Energy Journal*, 33(4), 1-22.

Huppmann, D. and Livingston, D. (2015). Stumbling to a new Equilibrium: understanding the current upheaval in the global crude oil market. *International Association for Energy Economics Energy Forum Index*, Third Quarter, 9-12.

Jaakkola, N. (2019). Carbon taxation, OPEC and the end of oil. *Journal of Environmental Economics and Management*, 94, 101-117.

Kisswani, K.M. (2016). Does OPEC act as a cartel? Empirical investigation of coordination behavior. *Energy Policy*, 97, 171-180.

Langer, L., Huppmann, D. and Holz, F. (2016). Lifting the US crude oil export ban: A numerical partial equilibrium analysis. *Energy Policy*, 97(C), 258-266.

Mahapatra, A. and Nanda, R. (2011). Bio-diesel and Bio-gas: Alternatives of the present. *Young Scientists Journal*, *4*(9), 4-6.

Mănescu, C and Nuño, G. (2015). Quantitative effects of the shale oil revolution. *Energy Policy*, 86, 855-866.

Okullo, S. J. and Reyes, F. (2016). Imperfect Cartelization in OPEC. *Energy Economics*, 60(C), 333-344.

Ortiz-Cruz, A., Rodriguez, E., Ibarra-Valdez, C. and Alvarez-Ramirez, J. (2012). Efficiency of crude oil markets: Evidences from informational entropy analysis. *Energy Policy*, 41(1), 365-373.

Reboredo, J., Rivera-Castro, M.A. and Ugolini, A. (2017). Wavelet-based test of co-movement and causality between oil and renewable energy stock prices. *Energy Economics*, 61, 241-252.

Reynolds, D.B. and Pippenger, M.K. (2010). OPEC and Venezuelan oil production: evidence against a cartel hypothesis. *Energy Policy*, 38, 6045-6055.

Wattanatorn, W. and Kanchanapoom, T. (2012). Oil Prices and Profitability Performance: Sector Analysis. *Procedia Social and Behavioral Sciences*, 40, 763-767.

Appendix

Proof of Lemma 1.

Plugging Q_i^{0*}, P^{0*} from equations (2) and (4) into the profit maximization function we obtain

$$\pi_i^{A*} = Q_i^{0*}\left(P^{0*} - c_i^0\right)$$

$$\pi_i^{A*} = \frac{(\alpha(2\beta-\gamma) - 2\beta c_i^0 - 2\beta^2(K_H^O + K_L^O) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O))^2}{16\beta - 8\beta\gamma}$$

where,

$$\frac{\partial \pi_i^{A*}}{\partial \gamma} = [-\frac{\left(-2\beta c_i^0 + \alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O)\right)}{4\beta(-2\beta^2+\gamma^2)^2}]\Big(2\alpha\beta(\beta-\gamma) + 2\beta\gamma c_i^0$$
$$+ \gamma^3\left(K_H^O + 2K_L^O\right) - 2\beta^2\left(\gamma(c_L^R + \gamma K_H^O + 3\gamma K_L^O)\right)\Big) < 0$$

The denominator is positive; hence, we focus our attention on the sign of the numerator. First, $\left(-2\beta c_i^0 + \alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O)\right)$ is positive if

$$c_L^R \geqslant \frac{\alpha(\gamma-2\beta) + 2\beta c_i^0 + 2\beta^2\left(K_H^O + 2K_L^O\right) - \gamma^2\left(K_H^O + 2K_L^O\right)}{\gamma} \equiv X.$$

Second, $\left(2\alpha\beta(\beta-\gamma) + 2\beta\gamma c_i^0 + \gamma^3\left(K_H^O + 2K_L^O\right) - 2\beta^2\left(\gamma(c_L^R + \gamma K_H^O + 3\gamma K_L^O)\right)\right)$ is positive if

$$c_L^R \leq \frac{2\alpha\beta(\beta-\gamma) + \gamma\left(2\beta c_i^0 - 2\beta^2\left(K_H^O + 3K_L^O\right) + \gamma^2\left(K_H^O + 2K_L^O\right)\right)}{2\beta^2} \equiv Y.$$

Hence $\frac{\partial \pi_i^{A*}}{\partial \gamma}$ is negative if and only if $c_L^R \epsilon [X, Y]$ which holds if Y⩾X, that is

$\frac{2\alpha\beta(\beta-\gamma) - 2\beta^2\left(K_H^O + 3K_L^O\right) + \gamma\left(2\beta c_i^0 + \gamma^2\left(K_H^O + 2K_L^O\right)\right)}{2\beta^2} \geqslant \frac{\alpha(\gamma-2\beta) + 2\beta c_i^0 + 2\beta^2\left(K_H^O + 2K_L^O\right) - \gamma^2\left(K_H^O + 2K_L^O\right)}{\gamma}.$

Solving for c_i^O, we get

$$c_i^O \leq \frac{\alpha\left(4\beta^3 - 2\beta\gamma^2\right) - 2\beta^2\gamma^2 K_L^O + \left(K_H^O + 2K_L^O\right)(\gamma^4 - 4\beta^4)}{4\beta^3 - 2\beta\gamma^2} \equiv \hat{c}_i^O.$$

For $P^{0*} > P^{R*}$ to hold in accommodate it must be that $\bar{c}_i^O$ (from equation (6)) is greater than $\hat{c}_i^O$.

$$\bar{c}_i^O - \hat{c}_i^O > 0.$$

Solving for α, we obtain

$$\alpha > c_L^R + \frac{4}{5}\beta\left(3K_H^O + 5K_L^O\right),$$

that is, the willingness to pay has to be sufficiently high for accommodate to be viable.

Proof of Lemma 2.

Plugging Q_i^{0*}, P^{0*} from equations (8) and (11) into the profit maximization function we obtain

$$\pi_i^{S*} = Q_i^{0*}\left(P^{0*} - c_i^0\right) + Q_i^{R*}\left(P^{R**} - c_i^R\right)$$

$$\pi_i^{S*} = \frac{(\alpha(\gamma - 2\beta) - 2\beta(\varepsilon - c_H^O) + 2\beta^2 K_L^O - \gamma(c_L^R + 2\gamma K_L^O))(c_i^0 + \varepsilon - c_H^O)}{2\beta^2 - \gamma^2}$$

where,

$$\frac{\partial \pi_i^{S*}}{\partial \gamma} = \frac{\left(c_L^R\gamma^2 - \alpha(2\beta^2 - 4\beta\gamma + \gamma^2) + 2\beta^2\left(c_L^R + 2\gamma K_L^O\right) + 4\beta\gamma\left(\varepsilon - c_H^O\right)\right)\left(c_H^O - \varepsilon - c_i^0\right)}{(-2\beta^2 + \gamma^2)^2}.$$

The denominator is positive for all parameter values, hence, $\frac{\partial \pi_i^{S*}}{\partial \gamma}$ is positive if the numerator is positive, which implies

$$c_L^R \geqslant \frac{\alpha(2\beta^2 - 4\beta\gamma + \gamma^2) - 4\beta\gamma\left(\varepsilon + \beta K_L^O - c_H^O\right)}{2\beta^2 + \gamma^2}.$$

Proof of Proposition 1.

$$\Delta\,\pi_i = \pi_i^{S*} - \pi_i^{A*}$$

Profits from squeeze and accommodate strategies are presented in lemma (2) and lemma (3) respectively. Hence,

$$\Delta\pi_i = \frac{\left(\alpha(-2\beta + \gamma) - 2\beta\left(\varepsilon - c_H^O\right) + 2\beta^2 K_L^O - \gamma\left(c_L^R + 2\gamma K_L^O\right)\right)\left(c_H^O - \varepsilon - c_i^0\right)}{2\beta^2 - \gamma^2} - \frac{(\alpha(2\beta - \gamma) - 2\beta c_i^0 - 2\beta^2(K_H^O + K_L^O) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O))^2}{16\beta - 8\beta\gamma}.$$

For $\Delta\,\pi_i$ to be positive it must be

$$K_H^O \geqslant \frac{\alpha(2\beta - \gamma) - 2\beta^2 K_L^O + \gamma\left(c_L^R + 2\gamma K_L^O\right) - 2\beta\left(c_i^0 + \sqrt{2}\sqrt{\frac{(c_i^0 + \varepsilon - c_H^O)(\alpha(-2\beta + \gamma) - 2\beta(\varepsilon - c_H^O) + 2\beta^2 K_L^O - \gamma(c_L^R + 2\gamma K_L^O))}{\beta}}\right)}{2\beta^2 - \gamma^2} \equiv \widehat{K}_H^O$$

Let us next examine under which conditions $\Delta\,\pi_i$ increases when both goods become more homogenous i.e., $\gamma \to \beta$.

$$\frac{\partial \Delta\pi_i}{\partial \gamma} = \frac{\left(\alpha(2\beta - \gamma) - 2\beta(2c_H^O - c_i^0 - 2\varepsilon) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O)\right)}{4\beta(\gamma^2 - 2\beta^2)^2} \times \frac{\left(2\alpha\beta(\beta - \gamma) - 2\beta\gamma\left(c_i^0 + 2\varepsilon - 2c_H^O\right) - 2\beta^2\left(c_L^R + \gamma K_H^O + 3\gamma K_L^O\right) + \gamma^3\left(K_H^O + 2K_L^O\right)\right)}{4\beta(\gamma^2 - 2\beta^2)^2}$$

The denominator is always positive, hence, we next focus on the numerator. From condition 1 we have that

$$\alpha(2\beta - \gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) > 2\beta(2c_H^O - c_i^0) > 2\beta(2c_H^O - c_i^0 - 2\varepsilon),$$

therefore, the first term in parenthesis is positive. Regarding the second term of the numerator, it is positive if

$$K_H^O > \frac{2\beta^2 c_L^R - 2\alpha\beta(\beta-\gamma) - 2\gamma^3 K_L^O - 2\beta\gamma\left(2c_H^O - c_i^0 - 2\varepsilon\right) + 6\beta^2\gamma K_L^O}{\gamma(\gamma^2 - 2\beta^2)} \equiv \widetilde{K_H^O} .$$

First not that the denominator is negative by definition. Hence, if the numerator is positive this condition is always satisfied and $\frac{\partial\Delta\pi_i}{\partial\gamma} > 0$. In particular, this numerator is positive if

$$2\beta^2 c_L^R - 2\alpha\beta(\beta-\gamma) - 2\gamma^3 K_L^O - 2\beta\gamma\left(2c_H^O - c_i^0 - 2\varepsilon\right) + 6\beta^2\gamma K_L^O > 0$$

To prove that this always holds we first check for the case where $\gamma \to 0$ to get interpretable results. For $\gamma \to 0$ we obtain $\widetilde{K_H^O} \equiv -c_L^R$. Since it is negative, therefore $K_H^O > 0$ is always satisfied. For $\gamma \to \beta$, $\widetilde{K_H^O} = \frac{2c_L^R - 2\left(2c_H^O - c_i^0 - 2\varepsilon\right) + 4\beta K_L^O}{-\beta}$. The denominator is negative, so we focus our attention on the numerator. The numerator is positive if $c_L^R > 2\left(c_H^O - \varepsilon\right) - c_i^0 - 2\beta K_L^O$. That is, if cost of renewable energy is sufficiently high, it implies that $\widetilde{K_H^O}$ is negative and therefore, $K_H^O > 0$ is always satisfied. Next, we examine under which conditions $\Delta\,\pi_i$ increases when production capacity of high cost producers increase.

$$\frac{\partial\Delta\pi_i}{\partial K_H^O} = \frac{\left[\alpha(2\beta-\gamma) - 2\beta c_i^0 - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O)\right]}{4\beta} > 0,$$

the denominator is positive by assumption. Hence, we focus on the numerator. To prove that it is positive we use condition (1) which states that

$$\alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) > 2\beta(2c_H^O - c_i^0)$$

where, $2\beta(2c_H^O - c_i^0) > 2\beta c_i^0$ for all parameter values, hence,

$$\alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) > 2\beta c_i^0.$$

Finally, we examine under which conditions $\Delta\,\pi_i$ increases when marginal cost of production of high cost producers increase.

$$\frac{\partial\Delta\pi_i}{\partial c_H^O} = \frac{\alpha(2\beta-\gamma) - 2\beta^2 K_L^O + \gamma(c_L^R + 2\gamma K_L^O) - 2\beta(2c_H^O - c_i^0 - 2\varepsilon)}{2\beta^2 - \gamma^2} > 0 .$$

We first focus on the denominator which is positive by assumption. Next, we focus on the numerator. From condition 1 we have

$$\alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) > 2\beta(2c_H^O - c_i^0)$$

where, $2\beta(2c_H^O - c_i^0) > 2\beta(2c_H^O - c_i^0 - 2\varepsilon)$. Hence, we obtain

$$\alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) > 2\beta(2c_H^O - c_i^0 - 2\varepsilon).$$

From Lemma 1 and Lemma 2 we know that profits decrease for both strategies as oil and renewable energy become homogeneous. To show that profits from accommodate are even lower than profits from squeeze when oil and renewable energy are completely homogeneous, we first focus on profits from accommodate

$$\pi_i^{\mathrm{A}*} = \frac{(\alpha(2\beta-\gamma) - 2\beta c_i^0 - 2\beta^2(K_H^O + K_L^O) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O))^2}{16\beta - 8\beta\gamma}.$$

When $\gamma \to \beta$ profits become,

$$\pi_i^{\mathrm{A}*} = \frac{(\alpha(2\beta-\gamma) - 2\beta c_i^0 - \beta^2 K_H^O + \beta c_L^R)^2}{8\beta(2-\beta)}.$$

The numerator is always positive. Hence, we next focus on the denominator, which is positive if and only if $\beta < 2$. Next, we look at profit from squeeze

$$\pi_i^{\mathrm{S}*} = \frac{(\alpha(\gamma-2\beta) - 2\beta(\varepsilon - c_H^O) + 2\beta^2 K_L^O - \gamma(c_L^R + 2\gamma K_L^O))(c_i^0 + \varepsilon - c_H^O)}{2\beta^2 - \gamma^2}.$$

When $\gamma \to \beta$

$$\pi_i^{\mathrm{S}*} = \frac{(2c_H^O - \alpha - c_L^R - 2\varepsilon)(c_i^0 + \varepsilon - c_H^O)}{\beta}$$

The denominator is always positive. Next, we focus on the numerator. Since $c_H^O > c_i^0 + \varepsilon$, hence, $c_i^0 + \varepsilon - c_H^O$ is negative for all parameter values. For profits to be positive, $2c_H^O - \alpha - c_L^R - 2\varepsilon$ must be also negative. Therefore, solving for c_L^R it yields $c_L^R > 2\left(c_H^O - \varepsilon\right) - \alpha$.

Lemma 3

We consider that the difference in output for the renewable good is

$$\Delta Q_L^{R*} = Q_L^{R*} \text{ (squeeze)} - Q_L^{R*} \text{ (accommodate)},$$

which implies,

$$\Delta Q_L^{R*} = -\frac{\gamma(\alpha(2\beta-\gamma) - 2\beta^2(K_H^O + K_L^O) + \gamma(c_L^R + \gamma K_H^O + 2\gamma K_L^O) + 2\beta(c_i^0 + 2\varepsilon - 2c_H^O))}{8\beta^3 - 4\beta\gamma^2}$$

$\Delta Q_L^{R*} > 0$ when $c_L^R < \frac{\alpha(\gamma-2\beta) - 2\beta(c_i^0 + 2\varepsilon - 2c_H^O) + 2\beta^2(K_H^O + K_L^O) - \gamma^2(K_H^O + 2K_L^O)}{\gamma} \equiv \tilde{c}$,

where, $\tilde{c}$ is positive if

$\alpha(\gamma - 2\beta) + 2\beta^2(K_H^O + K_L^O) - \gamma^2(K_H^O + 2K_L^O) - 2\beta(c_i^0 + 2\varepsilon - 2c_H^O) > 0$.

We can rewrite the equation as

$$\alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma^2\left(K_H^O + 2K_L^O\right) < 4\beta c_H^O - 2\beta c_i^0 - 4\beta\varepsilon. \qquad \text{(Z)}$$

Comparing it to condition (1) where we have that

$$\alpha(2\beta-\gamma) - 2\beta^2\left(K_H^O + K_L^O\right) + \gamma^2\left(K_H^O + 2K_L^O\right) \geqslant 4\beta c_H^O - 2\beta c_i^0 - \gamma c_L^R.$$

Therefore, (Z) does not hold if $4\beta c_H^O - 2\beta c_i^0 - \gamma c_L^R > 4\beta c_H^O - 2\beta c_i^0 - 4\beta\varepsilon$, which can be rewritten as $\gamma < \frac{4\beta\varepsilon}{c_L^R}$. Hence, $\tilde{c}$ is positive if and only if $\gamma \geq \frac{4\beta\varepsilon}{c_L^R}$. We next examine the following comparative statics,

$\frac{\partial \Delta Q_L^{R*}}{\partial \alpha} = \frac{\gamma(-2\beta+\gamma)}{8\beta^3-4\beta\gamma^2} < 0$ since $\beta^2 > \gamma^2$ by definition.

$\frac{\partial \Delta Q_L^{R*}}{\partial K_L^O} = \frac{\gamma(\beta-\gamma)(\beta+\gamma)}{4\beta-2\beta\gamma^2} < 0$ where the denominator is negative if $\gamma > \sqrt{2}$.

$\frac{\partial \Delta Q_L^{R*}}{\partial c_L^R} = -\frac{\gamma^2}{8\beta^3-4\beta\gamma^2} < 0$ since $\beta^2 > \gamma^2$ by definition.

Proof of Lemma 4.

Plugging Q_L^{0*}, P^{0*} from equation (14), (16), (17) and (18) into the profit function

$$\pi_L^{A,A*} = K_L^{0*}(P^{0*} - c_L^0) + Q_L^{R*}(P^{R*} - c_L^R)$$

$$\pi_L^{A,A*} = \frac{3{c_i^0}^2\gamma^2 + \alpha^2(5\beta^2 - 8\beta\gamma + 3\gamma^2) + 2\beta^3 c_i^0 K_H^O + \beta^4 {K_H^O}^2 - 2\beta c_i^0\gamma(4c_L^R + \gamma K_H^O)}{16(\beta^3 - \beta\gamma^2)}$$

$$+ \frac{\beta^2({c_i^0}^2 + 4{c_L^R}^2 - \gamma^2 {K_H^O}^2) - 2\alpha(\beta-\gamma)(-3c_i^0\gamma + \beta^2 K_H^O + \beta(c_i^0 + 4c_L^R + \gamma K_H^O))}{16(\beta^3 - \beta\gamma^2)}$$

Assuming $\beta = 1$and $\alpha = 1$,we obtain

$$\pi_L^{A,A*} = \frac{(c_L^R + \gamma - c_i^0\gamma)(-2 + 2c_L^R + \gamma(1 - c_i^0 + K_H^O))}{8(1-\gamma^2)} - \frac{(c_i^0 + K_H^O)(c_i^0 - 2c_L^R\gamma - \gamma^2 + c_i^0\gamma^2 + K_H^O - \gamma^2 K_H^O)}{16\gamma^2}$$

$\frac{\partial \pi_L^{A,A*}}{\partial c_L^R} = \frac{-\alpha\beta + \beta c_L^R + \alpha\gamma - c_i^0\gamma}{2(\beta^2-\gamma^2)} < 0$. The denominator is positive by assumption. Hence, we focus on the numerator which is negative if $\gamma < \frac{\beta(\alpha - c_L^R)}{\alpha - c_i^0}$. Considering $\beta = 1$and $\alpha = 1$,we obtain $\gamma < \frac{1-c_L^R}{1-c_i^0}$.

Proof of Lemma 5.

$$\pi_L^{S,S*} = K_L^{0*}(P^{0*} - c_L^0) + Q_L^{R*}(P^{R*} - c_L^R)$$

Using equation 31 and plugging $K_L^{0*} = \overline{K}_L^O, Q_L^{R*}$ and $P^{0*} = P_L^{O*} = c_H^O - \varepsilon$

$$\pi_L^{S,S*} = \overline{K}_L^O\left(c_H^O - c_i^0 - \varepsilon\right) + \frac{\beta\left(\beta c_L^R + \alpha(-\beta+\gamma) + \gamma\left(\varepsilon - c_H^O\right)\right)^2}{(-2\beta^2 + \gamma^2)^2}$$

Assuming $\beta = 1$ and $\alpha = 1$, we obtain

$$\pi_L^{S,S*} = \frac{\left(c_L^R + \gamma\left(1 + \varepsilon - c_H^O\right) - 1\right)^2}{\left(-2+\gamma^2\right)^2} - \overline{K}_L^O\left(c_i^0 + \varepsilon - c_H^O\right)$$

$$\frac{\partial \pi_L^{S,S*}}{\partial \gamma} = \frac{2\beta\left(\beta c_L^R + \alpha(-\beta+\gamma) + \gamma\left(\varepsilon - c_H^O\right)\right)\left(2\beta c_L^R\gamma + \alpha(2\beta^2 - 2\beta\gamma + \gamma^2) + 2\beta^2\left(\varepsilon - c_H^O\right) + \gamma^2\left(\varepsilon - c_H^O\right)\right)}{(2\beta^2 - \gamma^2)^3} > 0$$

The denominator is positive by definition. Hence, we focus on the numerator which is positive when $2\beta\left(\beta c_L^R + \alpha(-\beta+\gamma) + \gamma(\varepsilon - c_H^O)\right)(2\beta c_L^R\gamma + \alpha(2\beta^2 - 2\beta\gamma + \gamma^2) + 2\beta^2(\varepsilon - c_H^O) + \gamma^2(\varepsilon - c_H^O)) > 0$ which holds if

$$c_L^R > \frac{(2\beta^2+\gamma^2)(c_H^O - \varepsilon) - \alpha(2\beta^2 - 2\beta\gamma + \gamma^2)}{2\beta\gamma}.$$

Assuming $\beta = 1$ and $\alpha = 1$, we obtain

$$c_L^R > \frac{(2+\gamma^2)(c_H^O - \varepsilon) - (2 - 2\gamma + \gamma^2)}{2\gamma} \equiv \Omega$$

Proposition 2.

Plugging $\pi_i^{\text{S,S}*}$ and $\pi_i^{\text{A,A}*}$ from lemmas 4 and 5 and solving for $\Delta\pi_i > 0$ we have that

$$\Delta\pi_i = \pi_i^{\text{S,S}*} - \pi_i^{\text{A,A}*}$$

where

$$\Delta\pi_i = \frac{(\alpha(-2\beta+\gamma) + 2\beta^2\overline{K}_L^O - \gamma(c_L^R + \gamma\overline{K}_L^O) - 2\beta(\varepsilon - c_H^O))(c_i^0 + \varepsilon - c_H^O)}{2\beta^2 - \gamma^2} - \frac{\left(-\alpha + c_i^O + \beta K_H^O\right)^2}{8\beta},$$

which is strictly positive if the following condition is satisfied

$$c_L^R < \frac{(2\beta^2-\gamma^2)(8\beta\emptyset\left[2\beta(\varepsilon - c_H^O) - 2\beta^2\overline{K}_L^O + a\beta(2\beta-\gamma) + \overline{K}_L^O\gamma^2\right] + \vartheta(2\beta^2-\gamma^2))}{8\beta\gamma\emptyset(2\beta^3 - \beta\gamma^2)}.$$

where $\emptyset \equiv \left(c_i^0 + \varepsilon - c_H^O\right)$ and $\vartheta \equiv \left(-\alpha + c_i^O + \beta K_H^O\right)^2$. Assuming $\beta = 1$ and $\alpha = 1$,we obtain

$$\Delta\pi_i = \frac{((\gamma-2) + 2\overline{K}_L^O - \gamma(c_L^R + \gamma\overline{K}_L^O) - 2(\varepsilon - c_H^O))(c_i^0 + \varepsilon - c_H^O)}{2-\gamma^2} - \frac{\left(c_i^O - 1 + K_H^O\right)^2}{8}$$

which is positive if

$$c_L^R < \frac{(2-\gamma^2)(8\left(c_i^0 + \varepsilon - c_H^O\right)\left[2\left(\varepsilon - c_H^O\right) - 2\overline{K}_L^O + (2-\gamma) + \overline{K}_L^O\gamma^2\right] + (2-\gamma^2)\left(-1 + c_i^O + K_H^O\right)^2)}{8\gamma(c_H^O - c_i^0 - \varepsilon)(2-\gamma^2)}$$

$$\equiv \Psi.$$

We next examine under which conditions the low-cost OPEC also squeezes. From Lemma 5 we know that it chooses squeezes if $c_L^R > \Omega$. Hence, both OPEC and non-OPEC decide to squeeze if $\Psi > \Omega$, which holds if

$$\overline{K}_L^O > \frac{\left(1 + c_i^O + 2\varepsilon - 2c_H^O\right)^2 + 2(c_i^0 - 1)K_H^O + {K_H^O}^2}{8\gamma(c_i^0 + \varepsilon - c_H^O)}.$$

Note that the denominator is negative since $c_i^0 < c_H^O$, and ε is a negligible value. The denominator is positive if $2(c_i^0 - 1)K_H^O < {K_H^O}^2$, which implies that $2(c_i^0 - 1) < K_H^O$, which holds by definition since K_H^O is strictly positive and $c_i^0 \in (0,1)$. Therefore, $\Psi > \Omega$ for all values of $\overline{K}_L^O$.

Proposition 3.

We next examine the case in which the low-cost non-OPEC does not produce renewables but still influence price, assuming $\beta = 1$ and $\alpha = 1$.

Non-OPEC and OPEC accommodate

First, non-OPEC solves the following maximization problem

$$\max_{K_L^0} \pi_L^{A,A} = K_L^0[1 - \left(Q_i^0 + K_H^O + K_L^O\right) - c_i^O]$$

Taking first order conditions, we obtain

$$K_L^0\left(Q_i^O\right) = \frac{1 - K_H^O - c_i^O}{2} - \frac{Q_i^O}{2}$$

OPEC's solves the following maximization problem

$$\max_{Q_i^O} \pi_L^{A,A} = Q_i^O[1 - \left(Q_i^0 + K_H^O + K_L^0\left(Q_i^O\right)\right) - c_i^O]$$

which yields

$$Q_i^{O*} = \frac{(1-c_i^O)-K_H^O}{6} \text{ and } K_L^{0*} = \frac{(1-c_i^O)-K_H^O}{4}.$$

Hence,

$$P^{0*} = \frac{\left(1 + 3c_i^O\right) - K_H^O}{4}$$

and profits are

$$\pi_L^{A,A**} = \frac{\left(1 - c_i^O - K_H^O\right)^2}{16}$$

and

$$\pi_i^{A,A**} = \frac{\left(\alpha - c_i^O - K_H^O\right)^2}{8}$$

Non-OPEC and OPEC squeeze

We next examine the case in which both, OPEC and non-OPEC, squeeze. We focus on this case since we show that they do not have incentives to deviate to the opposite strategy when one of them choose squeeze. Hence, in this case both choose the price $P^{0*} = c_H^O - \varepsilon$ and profits become

$$\pi_L^{S,S**} = \overline{K}_L^O(c_H^O - c_i^O - \varepsilon) \text{ and } \pi_i^{S,S**} = (1 - c_H^O + \varepsilon - \overline{K}_L^O)(c_H^O - \varepsilon - c_i^O)$$

Therefore, in the absence of renewables, non-OPEC decides to squeeze if

$$\pi_L^{S,S**} \geq \pi_L^{A,A**}$$

And solving for c_H^O it implies that $c_H^O \geq \left(c_i^O + \varepsilon\right) + \frac{(c_i^O - 1 + K_H^O)^2}{16\overline{K}_L^O} \equiv \tilde{c}$. Similarly, OPEC decides to squeeze if

$$\pi_i^{S,S**} \geq \pi_i^{A,A**}$$

Which happens when

$$c_H^O \geq \frac{1}{4}\left(2c_i^O + 4\varepsilon + 2 - 2\overline{K}_L^O + \sqrt{2}\sqrt{(c_i^O - 1)^2 + 2(2\overline{K}_L^O - K_H^O)(c_i^O - 1) + (2\overline{K}_L^{O^2} - K_H^{O^2})}\right) \equiv \bar{c}\ .$$

Hence, both decide to squeeze when $c_H^O \geq \min\left[\left(c_i^O + \varepsilon\right) + \frac{(c_i^O - 1 + K_H^O)^2}{16\overline{K}_L^O}, \frac{1}{4}\left(2c_i^O + 4\varepsilon + 2 - 2\overline{K}_L^O + \sqrt{2}\sqrt{(c_i^O - 1)^2 + 2\left(2\overline{K}_L^O - K_H^O\right)(c_i^O - 1) + (2\overline{K}_L^{O^2} - K_H^{O^2})}\right)\right]$.

In addition, OPEC squeezes under larger condition when there is renewable than when no renewables are produced. That is,

$$\pi_i^{S,S*} \geq \pi_i^{A,A*}$$

Which happens when $c_H^O \geq \frac{2 + 2c_i^O + 4\varepsilon - \gamma + \gamma c_L^R - 2\overline{K}_L^O + \gamma^2 \overline{K}_L^O + 2(\gamma^2 - 1)\sqrt{R}}{4} \equiv \hat{c}$, where $R = \frac{1}{(-2-\gamma^2)^2}(2\gamma^2 - 4c_i^O\left(K_H^O - 2\overline{K}_L^O\right) + 2\gamma c_i^O\left(-2c_L^R + \gamma K_H^O - 2\gamma \overline{K}_L^O\right) - 2\left(K_H^{O^2} - 2\overline{K}_L^{O^2}\right) + \gamma^2\left(c_i^{O^2} + \left(c_L^R + \gamma \overline{K}_L^O\right)^2\right) + ((4\left(K_H^O + 2\overline{K}_L^O\right) - 4\left(c_i^O - \gamma \overline{K}_L^O\right) - 2\gamma^2\left(c_i^O + c_L^R + \gamma \overline{K}_L^O\right) + 2\gamma\left(2c_i^O + 2c_L^R - \gamma K_H^O + 2\gamma \overline{K}_L^O\ \right)) + (2c_i^{O^2} + \gamma(\gamma K_H^{O^2} - 4c_L^R \overline{K}_L^O - 4\gamma \overline{K}_L^{O^2}))$.

If we compare $\bar{c}$ and $\hat{c}$ we find that the latter is smaller than the former, i.e. $\hat{c} < \bar{c}$, when K_H^O is sufficiently high. In the case of low-cost non-OPEC, we also find that they squeeze under larger conditions since $\tilde{c}$ is higher than the condition on c_H^O guaranteeing that $\pi_L^{S,S*} \geq \pi_L^{A,A*}$. We do not present the calculations here since they are complex but can be provided upon request.