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OPEC and world oil security

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ABSTRACT

On the margin, the effectiveness of policy to enhance the stability of world oil market oil conditions greatly depends on which countries supply what economists would call the "marginal barrels." That is, the barrels whose production responds to changes in demand. If the countries dominating the production of the marginal barrels are relatively unstable, policies to reduce world oil consumption or boost oil production from stable suppliers will provide the additional benefit of reducing the contribution of unstable producers to the world oil market. If the countries dominating the marginal barrel are relatively stable, however, policies to reduce world oil consumption or boost oil production from stable suppliers will be less effective in promoting oil market stability.

Typically, we think of the highest cost producers as supplying the marginal barrel of oil, but our assessment finds it quite likely that OPEC dominates production of the marginal barrel of world oil. Moreover, OPEC members have been among the more unstable producers on a historical basis. Hence, reducing world oil consumption and promoting oil production in stable non-OPEC countries will enhance world oil security. Policies to promote stability in OPEC countries also would enhance world oil security.

1. Introduction

Recent declines in the price of oil are thought to fall the hardest on the highest cost oil sources of world oil consumption—such as Canadian tar sands and U.S. shale oil. Because these sources of oil supply are thought to be politically stable, analysts have expressed concern that lower oil prices will gradually reduce the security of world oil supply. Along these lines, we typically think of the highest cost producers as supplying the marginal barrels of world oil consumption—with the marginal barrels referring to the barrels of oil whose production is reduced or increased when demand falls or rises. The sources of the marginal barrels of oil can be important to policy because these sources of oil production most readily respond to changes in demand brought about by changes in policy.

Perhaps contrary to expectations, OPEC's low and relatively constant costs put it in a position where it can make an important contribution to the marginal barrel of world oil production through its exercise of market power.[1] To the extent that OPEC restrains its production to sustain higher world oil prices, it lessens its share of world oil production relative to competitive conditions. At the same time, OPEC's exercise of market power puts it in a position to contribute a significant portion of the marginal barrel of oil. That is, when confronted with a change in world oil demand, OPEC's exercise of market power provides it with the incentive to change its output—perhaps by more than non-OPEC producers.

Because OPEC members are also among the more unstable suppliers, OPEC's dominance in producing the marginal barrel of oil has important implications for world oil market security. Adelman (2004) suggested that these two seemingly disparate strands of inquiry need to be combined. Nonetheless, to our knowledge, the confluence of these issues has not been well examined or understood in the context of energy security. We find it worthwhile to examine both how OPEC's cost structure and behavior affects its contribution to the marginal barrel of oil, and to assess whether OPEC members have been among the unstable producers.

Our inquiry has important implications for energy policy. In assessing the security of world oil supply, we are concerned with two related issues: 1) Which countries produce the marginal barrels of oil;

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[1] We use the term "OPEC" for any large producing entity with the capacity to exert some degree of market power. It may be one country like Saudi Arabia or many countries like members of the Organization of the Petroleum Exporting Countries. Although defining which players can exercise their market power is critical for oil price projections, our analysis does not require that all OPEC member countries act collectively.

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and 2) Are the countries supplying the marginal barrels stable or unstable oil producers? The security of world oil supply and the effectiveness of policies to increase world oil security depend on the answers to these two questions. Policies to increase oil production in stable areas of the world or to reduce world oil consumption will be more effective at enhancing world oil security if they also reduce the production of unstable sources of oil production.

The remainder of the paper is organized as follows: Section 2 examines OPEC's role in global oil market instability. Section 3 examines OPEC's contribution to the marginal barrel of oil—taking into account costs and market structure while utilizing both static and dynamic analysis. Section 4 examines some options for increasing the security of world oil supply. Section 5 pulls these ideas together and examines the policy implications.

2. OPEC and the geopolitical instability of world supply

Brown and Huntington (2013, 2015) argue that global oil security increases when stable sources of world oil supply increase by more than unstable supplies. An increase in stable supplies by itself will not increase global security if its share of total world oil supply does not also increase. The historical record indicates that OPEC has maintained a relatively constant share of the world oil market in recent decades. But if that share should increase, global oil supplies would become more insecure because OPEC oil production appears to be more insecure than non-OPEC oil production in a geopolitical sense.

Evaluation of the historical record by a number of means shows that OPEC members have been among the politically unstable producers. Simple data analysis and an evaluation of oil supply volatility, by means of trend analysis using a Hodrick-Prescott filter, shows OPEC production has been less stable than non-OPEC production. Expert assessments also place OPEC members among the most unstable world oil producers. In addition, concerns about future political instability extend to members of OPEC that have been relatively stable in the past but are beginning to experience increasing political turmoil.

2.1. Historical data

When we look at raw data, OPEC production levels are substantially more volatile than for its non-OPEC counterpart. The most direct approach for evaluating this issue is to convert both OPEC and non-OPEC production to logarithms and calculate their first differences to derive annual growth rates.[2] The top set of results in Table 1 summarizes the variability of each group's annual production growth rate for the 1965–2013 period based upon annual data from the BP Review of Energy Statistics (British Petroleum 2014). Although each group's production grows by equal amounts (2.0% annually), OPEC's standard deviation of 7.5% greatly exceeds non-OPEC's standard deviation of 2.4%. The third column also confirms this finding by reporting normalized standard deviations, where the deviation in the second column is deflated by the mean in the first column. OPEC's production appears to be more than three times more volatile than non-OPEC's production.

This finding is also supported when the two series for production levels (rather than changes) are detrended to abstract from long-term trends. After detrending OPEC and non-OPEC oil production with a Hodrick-Prescott (1997) filter, we are able to express the variation (known as the cyclical effect within the context of the filter) as a percentage of the trended value. Actual and trended values for annual OPEC production are plotted in Fig. 1 and for annual non-OPEC production in Fig. 2. OPEC's normalized cyclical effect is 0.037, which is considerably higher than the 0.008 for non-OPEC. We applied the default Ravn–Uhlig rule for annual data to set the smoothing parameter. These estimates suggest that the volatility of OPEC production is more dramatic than for non-OPEC.

[2] In these computations, non-OPEC includes former Soviet Union areas, although excluding these regions does not change the conclusions.

Table 1
Volatility in oil production growth rates for various periods.
Sources: Authors' calculations based on annual data from BP Review of Energy Statistics and monthly data from U.S. Energy Information Administration.

	Mean	Std. Dev.	Normalized St. Dev.
1965–2013, Annual Data[a]			
OPEC	2.03%	7.52%	3.71
Non-OPEC	2.04%	2.36%	1.16
HP Trend[b]			
OPEC	26933	986	0.037
Non-OPEC	38780	324	0.008
1994–2013, Annual Data[a]			
OPEC	1.71%	3.84%	2.25
Non-OPEC	1.14%	1.08%	0.95
1994–2015, Monthly Data[c] (at annualized rates)			
OPEC	1.49%	19.33%	12.95
Non-OPEC	1.52%	10.45%	6.89

Notes:
[a] Annual data are first differences of natural logarithms expressed as a percentage.
[b] Cyclical variation from Hodrick-Prescott trend using levels data; mean production level is reported.
[c] Annual rate = $((1+\text{monthly rate})^{12})-1$, where the monthly rate is expressed in its decimal form.

The third set of results in this table repeat the same computations but restrict the analysis to the period beginning in 1994. These annual results cover the same period that will be evaluated with monthly data below. OPEC's production varies by almost four times more than non-OPEC's production, but it grows on average by more (1.7% per year rather than 1.1%). However, normalized standard deviation for OPEC production remains well more than twice that for non-OPEC production. For either period, OPEC's production appears to be much more volatile than that of its non-OPEC counterpart.

The last set of rows in Table 1 repeats the same computations for monthly data (from U.S. Energy Information Administration) over the period from January 1994 to February 2015 where the monthly estimates have been converted to annual rates. Once again, the average annual growth rates based upon the monthly data are very similar between the two groups, but OPEC's standard deviation is almost twice as large as that of non-OPEC. This finding also appears in the normalized standard deviations shown in the third column. Although the normalized standard deviations are much higher for the monthly than the annual data, the principal finding are the same. OPEC's production appears much more volatile than non-OPEC's.

2.2. Expert assessments

These empirical findings are supported by expert assessments. A study by the Council on Foreign Relations (2006) generally concluded that the greater political risks to world oil production lie in countries that are OPEC members. In addition, when geopolitical and military experts evaluated oil disruption risks for an Energy Modeling Forum study (Beccue and Huntington, 2016), they focused on Persian Gulf and other OPEC members in addition to Russia and some Caspian states. The primary motivation for restricting their focus to these producing areas is that most past oil supply disruptions have been caused by internal misgovernance ("failed states") or conflicts within or across OPEC nations.

The empirical results are further supported by analysis by the International Energy Agency (IEA, 2014), which concludes that major geopolitical and economic events in OPEC countries have been the source of most of the significant supply disruptions over the past seven decades. As shown in Table 2, the International Energy Agency

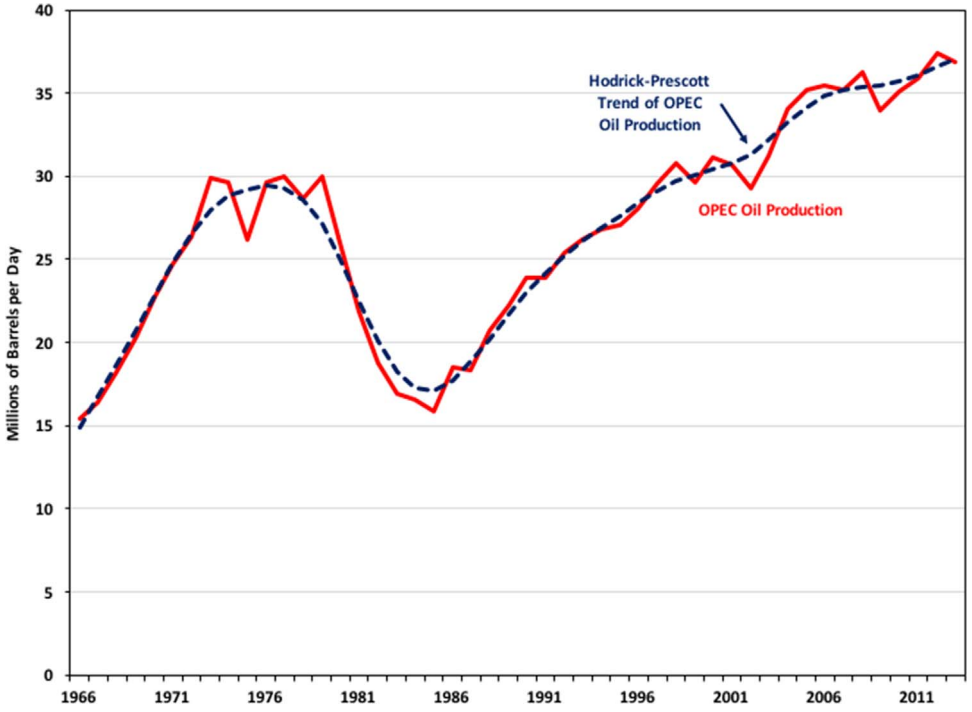

Fig. 1. OPEC annual oil production with Hodrick-Prescott trend.

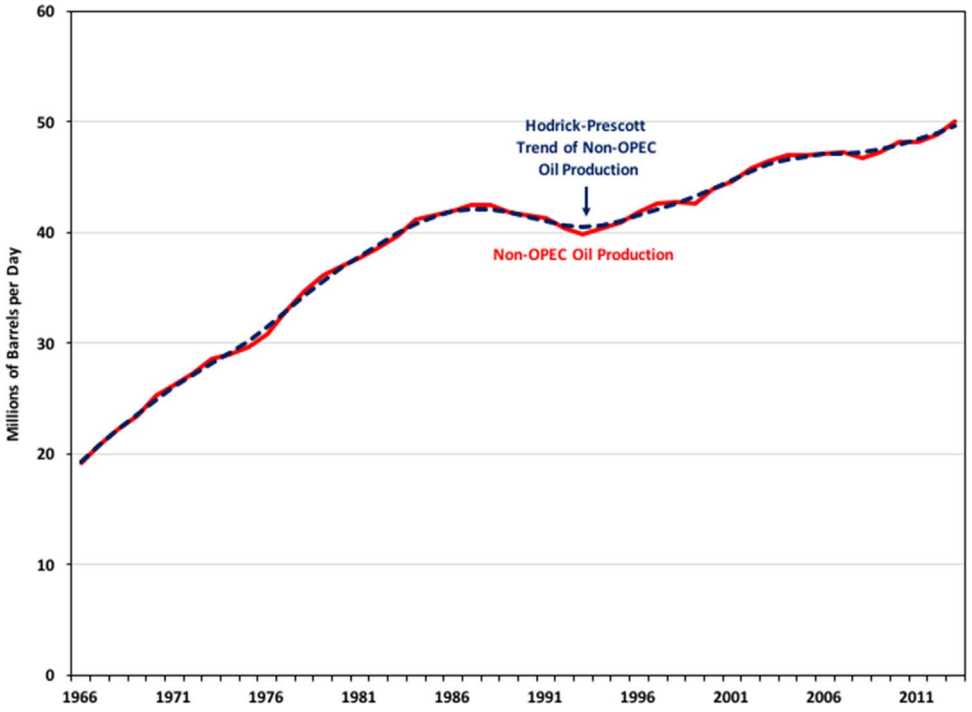

Fig. 2. Annual non-OPEC oil production with Hodrick-Prescott Trend.

identifies 12 major international oil supply disruptions since 1956.[3] As shown by this historical record, all but two brief hurricane-related disruptions are the result of geopolitical unrest in OPEC countries.

3. OPEC and the marginal barrel of oil

To some observers, OPEC appears to have lost near-term control of global oil market prices and outcomes. Weaker than expected world oil demand and surging U.S. oil production caused large price declines from 2014 into 2016 that followed an escalation of prices between 2004 and 2008. Unlike the early 1980s when Saudi Arabia cut its production in an effort to resist falling world oil prices, OPEC members have not tried to prevent oil price declines by reducing their output. Some pundits label these developments as evidence that OPEC has lost the ability to set world oil prices.

OPEC's behavior remains a matter of contention in the economics literature. Gately (2004, 2007) and Horn (2004) have used dynamic

[3] The U.S. Energy Information Administration (2015c) provides a somewhat similar list.

Table 2
Major oil supply disruptions.
Source: International Energy Agency (2014).

Event	Dates	Peak Disruption (million barrels per day)
Libyan Civil War	February to October 2011	1.5
Hurricanes Gustav and Ike	September 2008	1.3
Hurricanes Katrina and Rita	September 2005	1.5
War in Iraq	March to December 2003	2.3
Venezuelan Strike	December 2002 to March 2003	2.6
Iraqi Oil Export Suspension	June to July 2001	2.1
Iraqi Invasion of Kuwait	August 1990 to January 1991	4.3
Outbreak of Iran-Iraq War	October 1980 to January 1981	4.1
Iranian Revolution	November 1978 to April 1979	5.6
Arab-Israeli War and Arab Oil Embargo	October 1973 to March 1974	4.3
Six Day War	June to August 1967	2.0
Suez Crisis	November 1956 to March 1957	2.0

models to describe OPEC's best strategy for exporting crude oil and choosing prices that will maximize the present value of their potential future profits. A considerable body of research—such as Adelman (1972,1980,2004); Hnyilicza and Pindyck (1976); Pindyck (1978); Mead (1979); Moran (1982); Griffin (1985); Dahl and Yücel (1991); Gulen (1996); Okullo and Reynès (2016)—has provided assessments of OPEC's behavior that range from cartel to clumsy cartel, imperfect cartel and ineffective as a cartel. Smith (2009) argues that OPEC has been effective in restricting its capacity rather than limiting production within its capacity.

Current world oil market conditions seemingly do little to clarify OPEC's behavior in the world oil market. Looking at the current market, we might reach a number of different conclusions: 1) OPEC has collapsed to competitive behavior, and it will not resume its previous strategy of restricting its output once current market imbalances are eliminated; 2) OPEC has collapsed to competitive behavior, but it could resume restricting its production to promote higher world oil prices once current market imbalances are eliminated; or 3) OPEC is exercising market power and limit pricing while letting oil prices fall temporarily to reflect temporary imbalances in the market.

Combining Smith's perspective that OPEC is better at managing capacity than output with the Anderson et al. (2014) finding that oil producers have a limited ability to adjust the production in wells that have already been drilled, we favor the latter assessment. With weaker than anticipated world oil demand and the rapid expansion of high-cost production in North America, the world oil market is characterized by imbalances that result in losses for the high-cost producers. Rather than restricting its output to sustain the high prices necessary to maintain the profitability of high-cost producers, OPEC recognizes that its members are the low-cost producers, and it is pursuing a strategy of letting low oil prices gradually push the high-cost producers from the market.

We examine the implications of several different perspectives on OPEC's role in the world oil market. We first assess how production costs suggest who produces the marginal barrel. We then use static analysis to assess how OPEC would contribute to the marginal barrel if it behaves competitively or if it exercises market power to limit its capacity (and production) to obtain higher world oil prices. To confirm that our findings are not an artifact of the static approach, we also present the results of a dynamic modeling exercise in the appendix Dynamic Models of the World Oil Market.

3.1. Production costs and the marginal barrel of world oil

However we have reached current conditions, Fig. 3 represents a common perspective on the world oil market. Whether OPEC behaves competitively or restricts capacity, OPEC has the lowest production costs, and its costs per barrel are relatively constant as its output expands. Non-OPEC producers have higher unit costs, and those costs per barrel rise with increased production. The highest cost producers are likely shale oil producers in the United States.

With the relatively high prices that prevailed in 2014, the high-cost

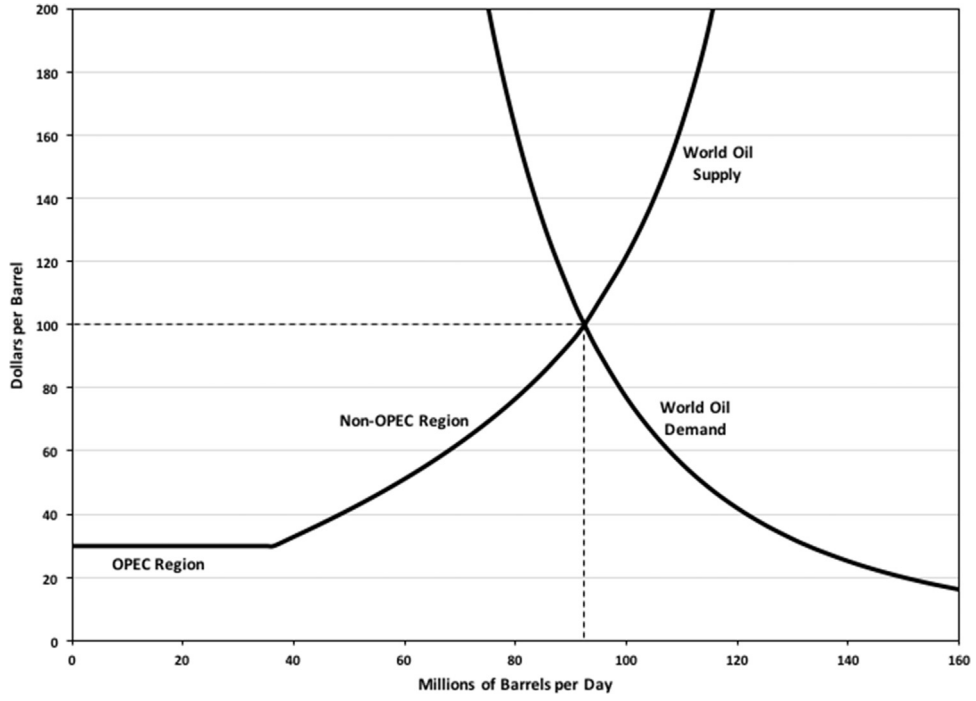

Fig. 3. World oil market.

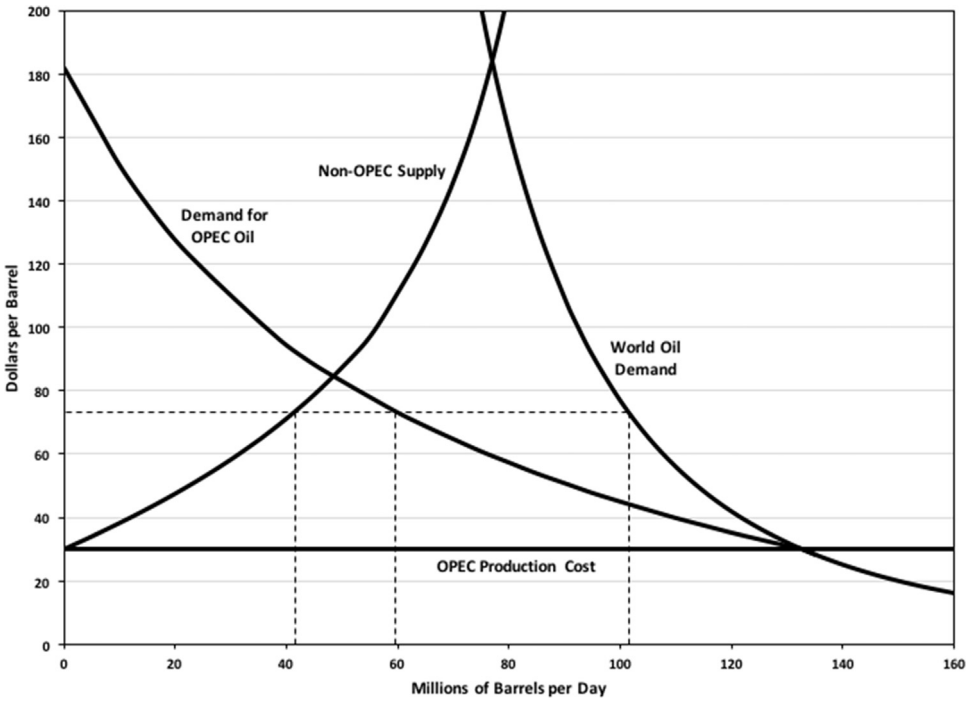

Fig. 4. OPEC and the world oil market.

producers were able to remain in the market. As prices sank, however, these high-cost producers began losing money. As their wells require reinvestment, these high-cost producers will be gradually pushed from the market. Hence, it appears as though the high-cost producers must be producing the marginal barrel(s) of world oil in the short run, and low-cost producers, such as OPEC, are not. That is, any change in demand will be met with only by changes in non-OPEC oil production.

3.2. OPEC acting competitively

The production-cost perspective emphasizes the short-run forces that determine the world oil price at any moment in time. If we are to consider the long-run forces shaping the world oil market, we must consider how OPEC countries determine their capacity and how those capacity decisions affect who produces the marginal barrel of oil production in the long run.

As shown in Fig. 4, the demand for OPEC oil is the difference between world oil demand and non-OPEC supply. Once OPEC determines its capacity (and production), the market price is reflected on OPEC's demand curve. World oil consumption and non-OPEC production are the respective quantities along the world oil demand curve and the non-OPEC supply curve.

OPEC can be envisioned as selecting any quantity along its production cost curve up to the point where world oil consumption equals OPEC production at its production cost. At that point, OPEC would only be able to charge its production costs.[4] So long as OPEC behaves competitively and sets its capacity (and production) below the point where it is providing all of world oil consumption, non-OPEC producers will be providing the entire marginal barrel of oil and OPEC will be contributing none.[5]

The simple static model breaks down, however, in determining how a competitive OPEC would set its capacity. Given OPEC's presumed cost advantages and estimated oil resources, OPEC could easily provide all or nearly all of world oil consumption rather than about 40%. If we believe that country risk or other costs limit OPEC's investment, we are implicitly assuming that OPEC has higher costs than are typically thought. If these costs rise with OPEC's capacity, OPEC members could easily be among the countries contributing to the marginal barrel of world oil production.

Alternatively, a dynamic analysis of the world oil market provides limits to OPEC capacity. OPEC sets its capacity (and production) in each period so that its marginal revenue equals marginal cost plus user costs, while it takes into account world oil demand and non-OPEC oil production. Non-OPEC oil producers also plan their production so that their user costs rise at the interest rate. With this analysis, we find a competitive OPEC would account for about 60% of world oil production.

3.3. OPEC's exercise of market power

The exercise of monopoly power is a common explanation for why OPEC might restrict its capacity (and production). If OPEC seeks to maximize profit, it will set its capacity and produce the quantity for which its marginal revenue equals its marginal cost, as shown in Fig. 5. If OPEC exercises monopoly power and restricts its capacity (and production) to increase prices, OPEC will also reduce its share of world oil production (or its contribution to the average barrel). As it reduces market share, however, OPEC will contribute to the marginal barrel of world oil production, which means both OPEC and non-OPEC oil production will respond to long-run changes in world oil demand.

We use a simple simulation exercise to illustrate how OPEC's contribution to the marginal barrel can be equal to or substantially greater than its market share. A standard approach to analyzing and simulating market conditions is to use demand and supply functions with constant price elasticities. Using this approach, world oil demand and non-OPEC supply can be written as:

$$Q_W = A \bullet P^{\eta_W} \quad (1)$$

$$Q_N = B \bullet P^{\eta_N} \quad (2)$$

where Q_W is the quantity of world oil demanded, A is a constant, η_W is the price elasticity of world oil demand, P is the world price of oil, Q_N is

[4] We are abstracting from user costs in this static analysis.

[5] A dynamic analysis yields substantially similar results. See the appendix, Dynamic Models of the World Oil Market.

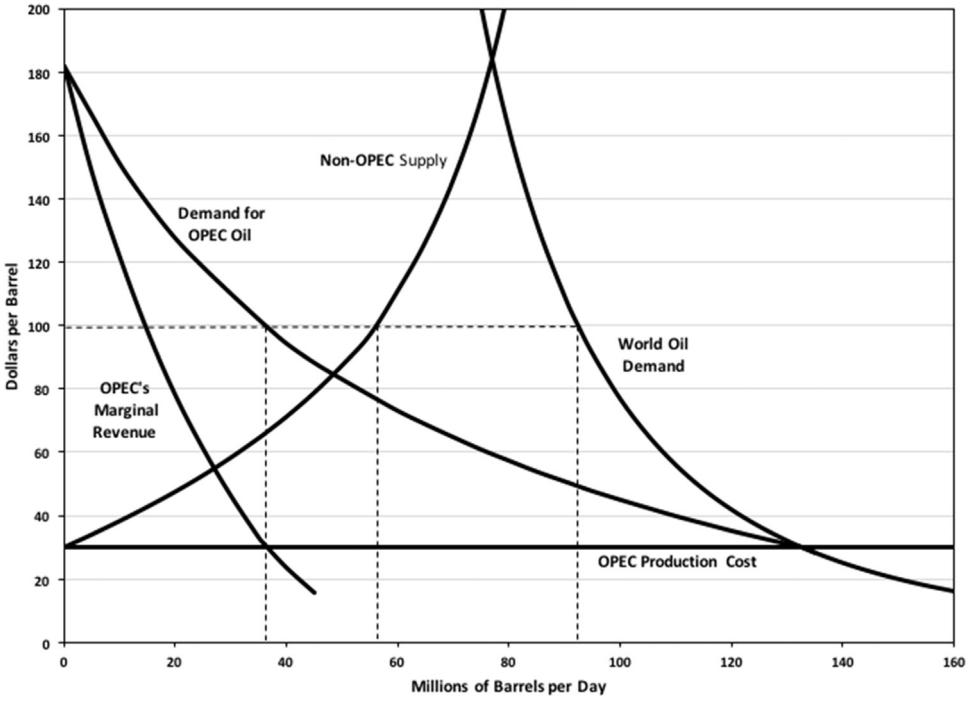

Fig. 5. OPEC's exercise of market power.

the quantity of non-OPEC oil supplied, B is a constant and η_N is the price elasticity of non-OPEC supply.

With these demand and supply functions, OPEC's marginal revenue is

$$MR = P + Q_O \frac{1}{A \bullet \eta_W \bullet P^{\eta_W - 1} - B \bullet \eta_N \bullet P^{\eta_N - 1}} \quad (3)$$

For purposes of this exercise, we allow OPEC's cost to vary with output rather than being constant for all output levels. If OPEC's cost elasticity is constant, its marginal cost function can be written as

$$MC = C \bullet Q_O^{1/\eta_{SO}} \quad (4)$$

where C is a constant and $1/\eta_{SO}$ is a parameter of OPEC's cost function.[6]

OPEC exercises its market power by equating marginal revenue (MR) and marginal cost (MC). Combining this balancing relationship with Eqs. (2)–(4) allows one to use a simple simulation exercise to find the quantity of OPEC production and to assess OPEC's contribution to the marginal barrel (Table 3). OPEC's contribution to the average world barrel of oil under pure monopoly conditions is unknown, but its share of world oil production was about 40% over the past five years, so we consider OPEC's exercise of market power with long-run elasticities and a market share of 40%.[7] We use long-run elasticities because OPEC's management of capacity (and production) is tied to long-run market adjustments as described above.[8] We also consider cost-elasticity parameters for OPEC oil production that range from equal to those of non-OPEC producers to much flatter costs and then to constant costs.

As shown in the table, OPEC's exercise of monopoly power will cause it to adjust production in response to long-run changes in demand, which means it contributes to the marginal barrel of oil.

Table 3
OPEC's market share and contribution to the marginal barrel as a monopoly. Sources: Illustrative values and authors' calculations.

Elasticities				OPEC	
OPEC's Cost Elasticity	Implied Long-Run Elasticity of OPEC Supply	Non-OPEC Long-Run Elasticity of Supply	World Long-Run Elasticity of Demand	Market Share	Contribution to the Marginal barrel
2.5	0.4	0.4	−0.4	40%	40%
1.25	0.8	0.4	−0.4	40%	50%
0.83	1.2	0.4	−0.4	40%	55%
0.1	10.0	0.4	−0.4	40%	65%
Constant	∞	0.4	−0.4	40%	67%

OPEC's response to a change in world oil consumption depends on its cost structure. As a monopoly producer with production costs that escalate with output at the same rate as those for non-OPEC suppliers, OPEC will provide 40% of the change in oil production in response to a change in demand—the same share on the margin that it supplies on average.

If OPEC's costs are flatter than those of non-OPEC producers, as is generally thought to be the case, it will supply a larger share of an increase in world oil consumption. With constant costs, OPEC is the dominant producer of the marginal barrel of oil. OPEC's oil production will adjust by two-thirds of an incremental increase in world oil consumption.

As these calculations show, OPEC's exercise of market power results in it contributing to the marginal barrel of oil. The flatter are OPEC's costs, the greater will be OPEC's contribution to the marginal barrel.[9]

The process of exercising market power to raise prices and profitability requires OPEC to reduce production, which decreases its market share. When OPEC is exercising market power, however, its profitability is more greatly affected by changing market conditions. With

[6] The variable η_{SO} would be the elasticity of oil supply for a competitive OPEC.

[7] As a well-performing cartel, OPEC's market share may be less than 40%.

[8] Consistent with Dahl's (2010a, 2010b) surveys, Hamilton (2009); Kilian and Murphy (2014) find the short-run elasticities that characterize the world oil market to be to be very low and close to zero. Following Dahl and Brown and Huntington (2015), we use long-run elasticities of demand and supply that are somewhat more elastic at −0.4 and 0.4, respectively.

[9] A dynamic analysis yields substantially similar results. See the appendix, Dynamic Models of the World Oil Market.

this increased sensitivity, maintaining profitability requires OPEC to vary its production more greatly in response to changes in market conditions. Consequently, OPEC's contribution to the marginal barrel will be increased. In addition, a cost structure that is more constant than that of non-OPEC producers would provide OPEC with a cost advantage in responding to increased demand.

3.4. OPEC's response to shifting market conditions

Many analysts see OPEC's role in the world oil market shifting with transitory and surprise changes in market conditions. OPEC seems to behave more competitively when world oil market conditions loosen as the result of weaker than expected demand or stronger than expected non-OPEC production. OPEC also seems to behave more like a cartel as world oil market conditions tighten. How might these changing conditions affect OPEC's response to market conditions?

If OPEC becomes less competitive as market conditions tighten, its market share is likely to become smaller and its contribution to the marginal barrel will be greater. Similarly, if OPEC becomes more competitive as market conditions loosen, its market share is likely to become greater and its contribution to the marginal barrel will be less.

3.5. OPEC's contribution to the marginal barrel

We find that OPEC's market behavior greatly affects its market share and its contribution to the marginal barrel of world oil production. A competitive OPEC would likely have a large market share, but it would contribute relatively little to the marginal barrel of world oil production. If OPEC has relatively constant costs, its exercise of market power reduces its market share while increasing substantially its contribution to the marginal barrel.

OPEC may shift its behavior with market conditions, increasing its use of market power when markets are tighter. As OPEC increases its use of market power, it will reduce its market share and increase its contribution to the marginal barrel.

4. Increasing the security of world oil supply

To the extent it exercises market power, OPEC is an important contributor to the marginal barrel of oil, and OPEC production has been unstable historically. Given these findings, the oil-importing nations have several options for increasing global oil security. They can reduce oil demand. They can increase non-OPEC supply, and they can also promote stability in OPEC member nations.

Reduced world oil demand or increased production of non-OPEC oil would be effective in reducing OPEC's contribution to the world oil market. If OPEC exercises monopoly power and has constant costs, each reduction in world oil consumption will result in a reduction of OPEC oil production equal to 67% of the reduction in world oil consumption according to static analysis.[10] In a similar vein, increased non-OPEC oil production will reduce OPEC's share of the world oil market and would help with world oil market stability.

Another option for the oil-importing nations is to promote economic and political stability among OPEC member nations. Such an approach might require that the oil-importing nations shift from treating OPEC members as inexpensive sources for oil imports toward policies that help the countries make a transition toward more inclusive governance and the development of more diverse economies.

5. Conclusions and policy implications

In this paper, we develop a framework for evaluating the critical factors influencing OPEC's role in the world oil market and its geopolitical record of unstable production. Our approach is to combine to seemingly disparate strands of inquiry as Adelman (2004) suggested. With this approach, we are able to assess how policies to change global oil demand and non-OPEC supply will affect world oil supply security in a geopolitical sense.

We find OPEC's cost structure and likely market behavior has made it the dominant producer of the marginal barrel of oil, which means OPEC will account for a large share of the adjustment in world oil production to changes in demand. OPEC's exercise of market power reduces its market share while increasing its contribution to the marginal barrel. Therefore, OPEC's relatively low cost structure and exercise of market power likely has obscured its role as the dominant supplier of the marginal barrel.

We also find OPEC members have been among the more unstable producers, and they can be expected to remain so. Consequently, OPEC's low costs and market dominance contribute to the insecurity of world oil supply.

The weakness of current oil prices also raises concerns about the possibility of increased world oil consumption and reduced oil production from secure, high-cost sources such as the Canadian tar sands and U.S. shale oil. To some extent these concerns are borne out by our analysis. Future increases in world oil demand will draw heavily on OPEC oil production, which has been among the more unstable sources of world oil supply.

These findings have implications for world oil security. To the extent that OPEC exercises market power, reducing global oil consumption or promoting the oil production from stable sources outside OPEC would increase world oil security. Increasing the stability of OPEC member nations also would help increase the stability of world oil supply.

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Appendix A. Dynamic models of the world oil market

To further examine how OPEC's behavior affects its contribution to the marginal barrel of oil, we also developed dynamic simulations models of the world oil market under the assumptions that OPEC behaves competitively and as a monopolist. These models yield substantially similar results to those found with the static analysis. As OPEC exercises market power, it reduces its market share of world oil production but it increases its share of the marginal barrel.

We use several dynamic models of the world oil market. One model is built with the idea that OPEC and non-OPEC producers behave competitively. The other model is built with the idea that OPEC exercises market power, but non-OPEC producers are price takers. Both models use a backstop technology that establishes a maximum crude oil price of $232.53 per barrel (in 2013 dollars), and both models show OPEC with constant costs, and non-OPEC producers with increasing marginal costs.

[10] Dynamic analysis shows similar results.

For the purposes of examining OPEC's contribution to the marginal barrel of oil, we can represent the world oil market as consisting of consumers who are supplied by OPEC, non-OPEC oil producers, and eventually by a backstop technology, such as electric or hydrogen powered vehicles, that will serve as a perfect substitute for oil when oil prices are sufficiently high in the future. Both OPEC and non-OPEC oil producers have exhaustible oil resources, but the backstop is infinite in quantity and elasticity.

A.1 World oil demand and non-OPEC supply

The evolution of world oil consumption may be conceived as a function of price, aggregate economic activity and technology.

$$Q_{Wt} = Q_W(P_t, Y_t, T_t) \tag{A.1}$$

where Y_t is a measure of aggregate world output (such as world GDP) at time t, and T_t is the state of technology at time t.

For a given price path, the profit maximizing conditions for non-OPEC oil production can be summarized as:

$$max\Pi_N = \int_{t=0}^{\infty} e^{-rt}(P_t Q_{Nt} - C_{Nt}(Q_{Nt}))\partial t \tag{A.2}$$

$$\text{s. t.} \int_{t=0}^{\infty} Q_{Nt}\partial t = \overline{Q}_N \tag{A.3}$$

where Π_N is the present value profit associated with non-OPEC oil production, C_{Nt} is the total cost of non-OPEC oil output at time t, and the cumulative production of non-OPEC oil must be equal to its total oil resource endowment ($\overline{Q}_N$)—the latter including only the resource can be profitability produced at a price below or equal to the backstop price ($\overline{P}_B$).

A.2 With a competitive OPEC oil supply

For a given price path, the profit maximizing conditions for competitive OPEC oil production can be summarized as:

$$max\Pi_O = \int_{t=0}^{\infty} e^{-rt}(P_t Q_{Ot} - C_{Ot}(Q_{Ot}))\partial t \tag{A.4}$$

$$\text{s. t.} \int_{t=0}^{\infty} Q_{Ot}\partial t = \overline{Q}_O \tag{A.5}$$

where Π_O is the present value profit associated with OPEC oil production, C_{Ot} is the total cost of OPEC oil output at time t, and the cumulative production of OPEC oil must be equal to its total oil resource endowment ($\overline{Q}_O$)—the latter including only the resource can be profitability produced at a price below or equal to $\overline{P}_B$.

In addition,

$$Q_{Wt} = Q_{Ot} + Q_{Nt} + Q_{Bt} \tag{A.6}$$

Total world oil consumption (Q_{Wt}) at any moment in time is equal to OPEC oil production Q_{Nt}), non-OPEC oil production (Q_{Nt}) and production of the backstop (Q_{Bt}).

Pontryagin's maximum principle establishes familiar conditions for present value profit maximization for non-OPEC oil producers:

$$P_t = \frac{\partial C_{jt}}{\partial Q_{jt}} + \lambda_{jt} \quad \text{for j} = N,\ O \text{ and all } t \text{ such that } P_t \leq \overline{P}_B \tag{A.7}$$

where λ_{Ot} is the user cost associated with OPEC oil production at time t, and λ_{Nt} is the user cost associated with non-OPEC oil production at time t, and $\overline{P}_B$ is the backstop price. Both λ_{Ot} and λ_{Nt} evolve with the interest rate.[11] Both OPEC and non-OPEC producers organize their production based on the prices set by OPEC such that the value of holding a marginal unit of its oil for production in a future period has the same present value as producing it today. Because the model does not have a steady state, it is solved as a simulation through an iterative search on the initial values of λ_{Ot} and λ_{Nt} that generate trajectories of OPEC and non-OPEC oil production and timing of the exhaustion of their resources.

A.3 With OPEC exercising market power

As a dynamic market actor that exercises market power, OPEC's objective is to establish a trajectory for world oil prices that maximize its present value profits. In setting such a price path, OPEC must take into account the response of consumers and non-OPEC oil producers, and the future use of the backstop technology. Consumers, non-OPEC oil producers and the backstop producers are price takers, with the consumers and producers responding to the oil price at each moment in time and the backstop producers responding only when world oil prices are sufficiently high.

OPEC's present value profit maximizing conditions can be described as:

$$max\Pi_O = \int_{t=0}^{\infty} e^{-rt}(P_t(Q_{Ot})Q_{Ot} - C_{Ot}(Q_{Ot}))\partial t \tag{A.8}$$

$$\text{s. t.} \int_{t=0}^{\infty} Q_{Ot}\partial t = \overline{Q}_O \tag{A.9}$$

[11] The evolution of user costs depends upon how depletion and experience affect production costs. In the absence of depletion costs or learning from production, user costs rise at the interest rate such that $\frac{\partial \lambda_{jt}}{\partial t} = r$. See Peterson and Fisher (1977).

$$P_t \leq \overline{P}_B \tag{A.10}$$

where Π_O is the present value profit associated with OPEC oil production, r is the discount rate, P_t is the world price of oil at time t, Q_{Ot} is OPEC's oil production at time t, and C_{Ot} is the total cost of OPEC's oil output at time t.

The demand conditions and the profit maximizing conditions for non-OPEC producers remain as described in Eqs. (A.1)–(A.3) with the consumers and non-OPEC producers responding to the price trajectory set by OPEC. Eq. (A.6) can be rewritten as

$$Q_{Ot} = Q_{Wt} - Q_{Nt} - Q_{Bt} \tag{A.11}$$

OPEC's oil production at any moment in time is equal to total world oil consumption (Q_{Wt}) less non-OPEC oil production (Q_{Nt}) and production of the backstop (Q_{Bt}).

For non-OPEC producers, the profit maximizing conditions remain as described in (A.7). Non-OPEC producers organize their production based on the prices set by OPEC such that the value of holding a marginal unit of its oil for production in a future period has the same present value as producing it today.

Pontryagin's maximum principle yields somewhat more complex profit maximizing conditions for OPEC:

$$P_t + Q_{Ot}\left(\frac{\partial P_t}{\partial Q_{Ot}}\right) = \frac{\partial C_{Ot}}{\partial Q_{Ot}} + \lambda_{Ot} \text{ for all } t \text{ such that } P_t < \overline{P}_B \text{ or } P_t \text{ initially reaches } \overline{P}_B \tag{A.12}$$

and

$$P_t \geq \frac{\partial C_{Ot}}{\partial Q_{Ot}} + \lambda_{Ot} \geq P_t + Q_{Ot}\left(\frac{\partial P_t}{\partial Q_{Ot}}\right) \text{ for all } t \text{ such that } P_t = \overline{P}_B \tag{A.13}$$

and

$$Q_{Ot} = Q_{Wt}(P_t) - Q_{Nt}(P_t) - Q_{Bt}(P_t) \text{ for all } t \tag{A.14}$$

where λ_{Ot} is the user cost associated with OPEC oil production at time t.

In each moment in time during which the oil price is less than or initially reaches the backstop, the conditions for maximizing OPEC's present value profit occur when marginal revenue equals the marginal cost of production plus user cost. OPEC sets its user cost by taking into account its ability to exercise monopoly power when the world oil price is less than or first reaches the backstop price and the value of saving its oil for production at the backstop price. That is, OPEC takes into account the effects of its pricing decisions on world oil consumption, non-OPEC production, and the economic viability of the backstop technology, and increases world oil prices over time in such a way that the value of holding a marginal unit of its own oil for production in a future period in which the price is less than or initially reaches the backstop price has the same present value as producing it today.

Once the backstop price is reached, however, OPEC changes its production and pricing strategy. OPEC adjusts its production to make sure the backstop price is sustained.[12] OPEC sets its production such that marginal cost plus user cost is less than or equal to price and greater than or equal to marginal revenue (where marginal revenue is related to the demand for OPEC oil in the absence of the backstop technology). Subject to these pricing constraints, OPEC will produce the difference between world oil consumption and non-OPEC oil production, crowding out production of the backstop until its (OPEC's) oil resources are depleted. As OPEC ceases production and non-OPEC oil is gradually depleted, production of backstop will grow.[13]

Because the model does not have a steady state, it is solved as a simulation through an iterative search on the initial values of λ_{Ot} and λ_{Nt} that generate trajectories of OPEC and non-OPEC oil production and timing of the exhaustion of their resources.

A.4 Model parameters and assumptions

We set the marginal cost of OPEC's oil output, including exploration, development and production, at a constant $30 per barrel (in 2013 U.S. dollars). Using information from EIA (2015a, 2015b) and GEA (2012), we placed OPEC's total conventional oil resources in place at 1652.687 billion barrels. We assume OPEC uses a real discount rate of 4.0% in its decision making.[14]

For non-OPEC oil producers, we assumed the marginal cost of daily production in any year could be described by the function $MC_N = (\frac{Q_N}{K})^{\frac{1}{\eta_N}}$, where MC_N is the marginal cost of non-OPEC production in year, Q_N is the quantity of non-OPEC production, K is a constant determined in model calibration, and η_N is a parameter that describes how non-OPEC costs increase with production. In the absence of user costs, η_N would be the price elasticity of non-OPEC supply for daily production in any given year. With user costs, however, the price elasticity of non-OPEC supply is somewhat greater than η_N.[15]

Our review of the empirical literature on world oil supply (See Brown and Huntington, 2015) combined with model calibration yielded a value of η_N equal to 0.425. Using information from EIA (2015a, 2015b) and GEA (2012), we placed non-OPEC's total oil resources in place at 2537.937 billion barrels, including tar sands and shale oil. As we did with OPEC, we assume non-OPEC oil producers use a real discount rate of 4.0% in their decision-making process.

Given that most petroleum products are consumed in transportation, we followed the National Research Council (2013) evaluation of alternative transportation fuels and picked hydrogen fuel as the backstop technology for oil. To obtain sufficient quantities, the hydrogen is produced from

[12] We follow Salant (1977) and assume that oil producers have the first opportunity to provide oil at the backstop price, and the backstop technology is only used to fill in the difference between world oil consumption and production. Our approach avoids the kinked demand curve of Dasgupta and Stiglitz (1981).

[13] If non-OPEC oil production is characterized by increasing marginal costs, non-OPEC producers schedule some of their production for time periods after world oil prices reach the backstop as a way to reduce costs.

[14] A 4% rate approximates the average real rate on U.S. 30-year Treasury bonds over the past four decades (U.S. Office of Management and Budget, 2015). Businesses typically use higher rates, and some economists recommend using lower social rates of discount for evaluating environmental and resource issues. The results are not qualitatively sensitive to plausible values of the assumed discount rate.

[15] In particular, the price elasticity of non-OPEC supply for any period is equal to $\eta_N \cdot (P_t/(P_t - \lambda_{Nt}))$.

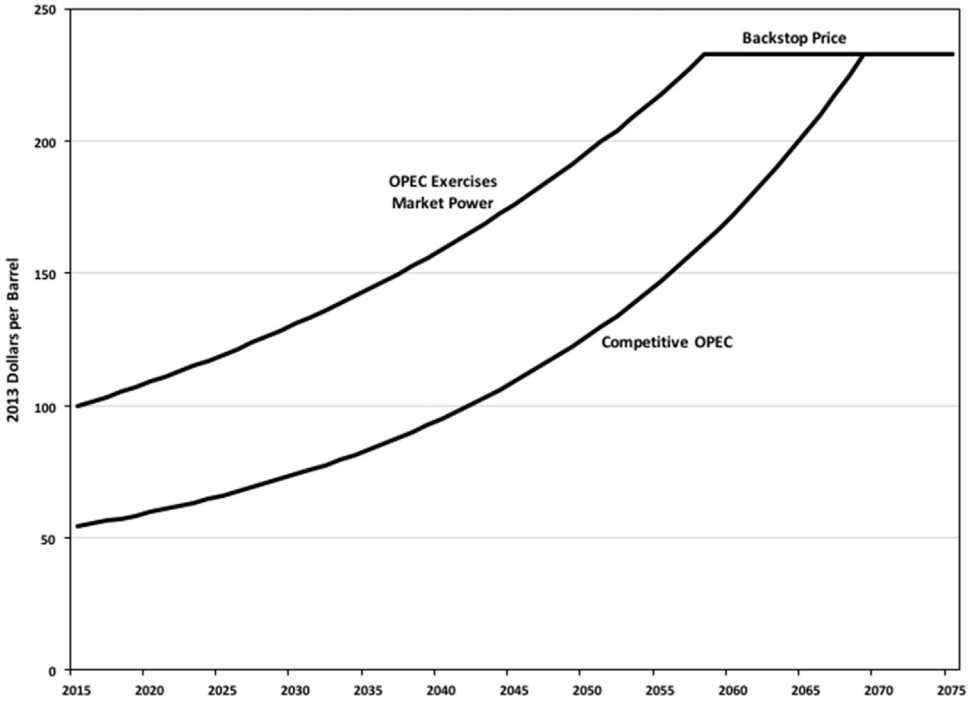

Fig. A1. Projected world oil prices.

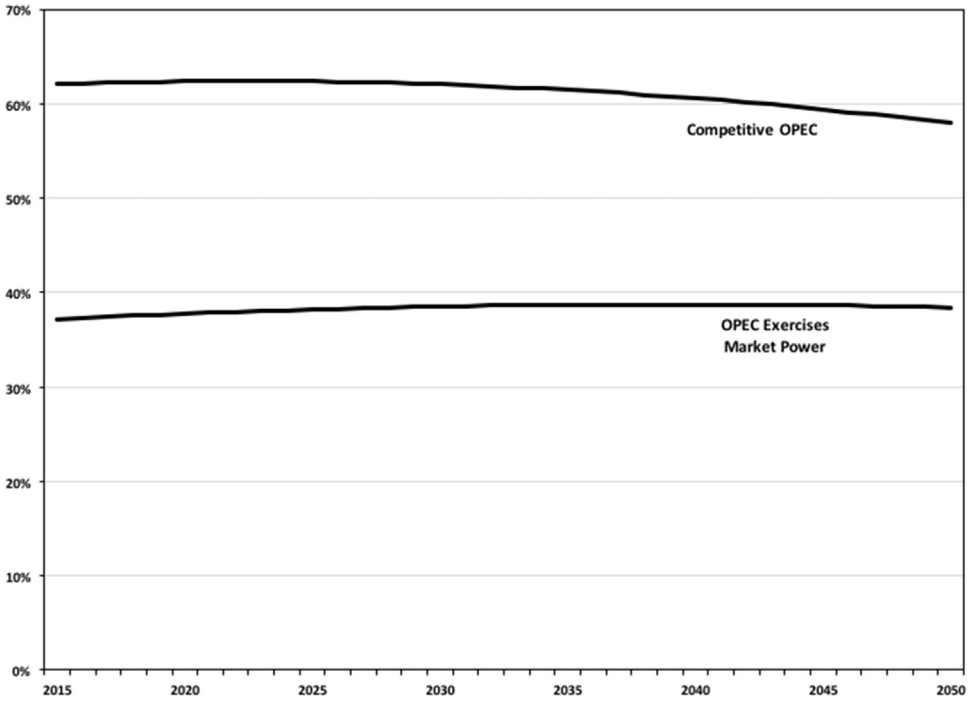

Fig. A2. OPEC's projected market share.

water through the use of electricity. The National Research Council (2013) provides estimates of the costs of producing hydrogen from water using electricity and the higher capital costs of vehicles designed to use hydrogen rather than petroleum products. With those costs and an estimate of the historical relationship between gasoline prices and crude oil prices, we place a price of $232.53 per barrel (in 2013 U.S. dollars) on the backstop technology. At this price, conventional oil can be sold side-by-side with hydrogen. At any lower price, no hydrogen is sold for use as a transportation fuel. Any attempt to set a higher price would cause the model to hold the price constant at the backstop with hydrogen displacing petroleum products from the market.

A.5 Model calibration

The model was initially calibrated to approximate the world oil market conditions that the U.S. Energy Information Administration (EIA) projects in its *2014 International Energy Outlook* (IEO). Matching the outlook required setting the parameters of the model for a loose cartel,

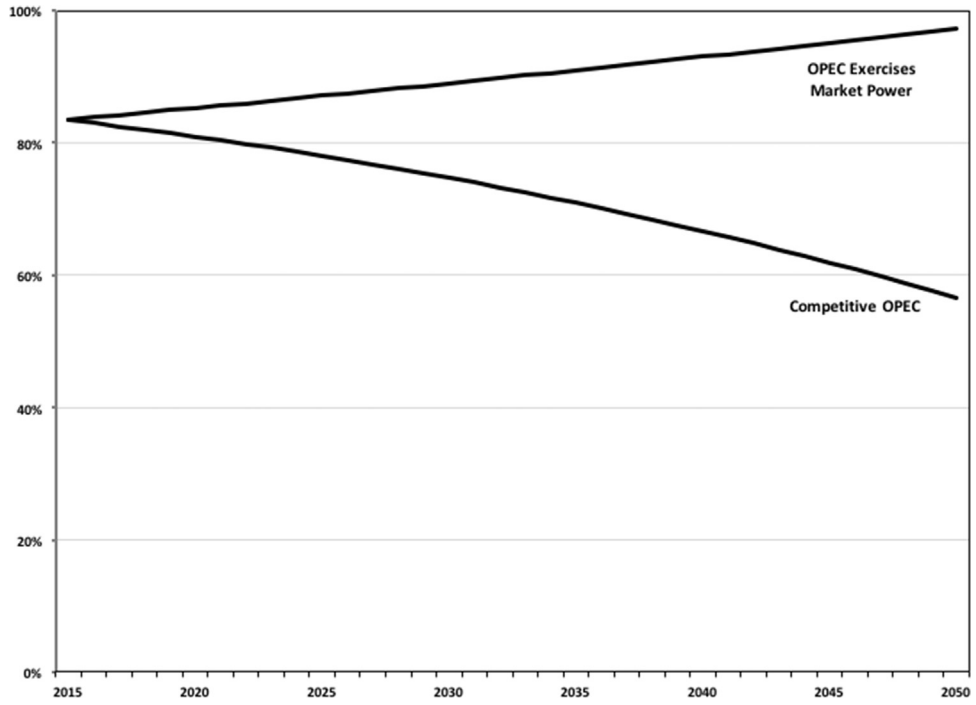

Fig. A3. OPEC's contribution to the marginal barrel.

which meant that OPEC produced somewhat more oil in the first 40 years than yields present value profit maximization. The model parameters were then reset to produce a competitive case in which OPEC simply takes world oil prices and behaves like another competitive supplier and a monopoly case in which OPEC acts to maximize its present value profit.

A.6 A dynamic analysis of OPEC and the world oil market

Fig. A1 shows the price paths for the two scenarios generated by the two dynamic models. As in Stiglitz (1976) and Sweeney (1977), the oil price path is lower and increases at a faster rate with OPEC behaving competitively rather than exercising market power. With OPEC behaving competitively, the price of crude oil rises from $54.36 per barrel (in 2013 dollars) in 2015 until it hits the backstop price of $232.53 per barrel in 2069. With OPEC exercising market power, the price of crude oil rises from $99.76 per barrel (in 2013 dollars) in 2015 until it hits the backstop price of $232.53 per barrel in 2058. The backstop prevents a solution in which the more rapid depletion occurring under competition results in the competitive price eventually rising above the monopoly price.

As shown in Fig. A2, the dynamic model shows that a competitive OPEC would produce more than 60% of world oil from 2015 through 2043. OPEC's market share gradually diminishes after 2022, reaching 58% in 2050. In contrast, the dynamic model shows that OPEC's exercise of market power reduces its market share below 40% from 2015 through 2050.

As shown in Fig. A3, the dynamic model finds results that are similar to the static analysis in Section 3 above. Over the 2015-50 time horizon, a competitive OPEC would contribute a smaller share of the marginal barrel than an OPEC that exercises its market power. Although the exercise of market power reduces OPEC's average market share to less than 40%, OPEC will adjust its production considerably in response to a permanent change in world oil demand. The model shows OPEC contributing more than 80% of the change in consumption in 2015 with growth to nearly 100% of consumption in 2050.

In contrast, the dynamic model yields somewhat different results for a competitive OPEC than the static analysis. For a permanent change in world oil demand, the model shows OPEC contributing more than 80% of the change in consumption in 2015, but the contribution declines sharply over the next 35 years—falling to just over 55% in 2050. A competitive OPEC would adjust its production in response to a permanent change in world oil demand by more than it market share, but by less than if it were exercising market power.

The exact responses depend on demand, OPEC's and non-OPEC's costs. Nonetheless, OPEC's exercise of market power will reduce its share of world oil production and increase its contribution to the marginal barrel.

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