The Oil Games

Episode 3—November 25, 2017

OPEC Market Share Explained by Game Theory

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The Oil Games is a series of interconnected episodes in which we explain market behavior using Kayrros' extensive knowledge of the energy industry, mathematics, and game theory in particular. The series' target audiences include the practitioners, investors, and observers of the oil industry who are interested in finding new ways of understanding this fascinating business. The authors are Jean-Michel Lasry, Antoine Halff, and Antoine Rostand. This is an ongoing story with future episodes being published in sequence by Kayrros.

Summary: Using Game Theory to Explain the Stability of OPEC Market Share

In the first two episodes of the Oil Games, we met the Players, discovered the Rules of the Game, and began to understand the strategies of the various Players. We understood that oil and gas discoveries just like any other technological innovation were first and foremost a matter of financing. We asked ourselves the question what drives investors to allocate funding to the pursuit of discovery and found that the answer was just the same as in any other business, namely the expected return on investment. But we also understood that shale oil changed the rules. Is shale oil indeed the ultimate realization of Schumpeter's promise? Is it really a break from the past, or is it a flash in the pan and just like any other source of oil?

Episode 3 starts addressing these crucial questions. We will go step by step to understand how both game theory and economic analysis move the invisible hand that guides the behavior of the Players to lead to a remarkably stable OPEC market share.

We will find that OPEC's market share has a sweet spot that is neither too high, nor too low. It is just right. **We will demonstrate that OPEC does not target a price but adjusts its production volume to maximize its profit while leveraging high-cost production from non-OPEC members for maximum benefit.** This finding is supported by 30 years of recent OPEC history and it will likely go a long way toward explaining its future.

As all commodity traders know very well, understanding the strategic behavior of a group of producers is complex. The standard economic assumption is one of open competition in a market in which each player is completely transparent. The reality, however, is that the positions and relationships are both many and highly diverse. The market players are not just trading for their own account as it were, but can band together and form relationships with one another that range from monopolies to oligopolies to other forms of coalition—all of which can give them some kind of competitive advantage.

Although states can prohibit industrial actors from engaging in monopolistic behavior, there is no international body that can bar such behavior at the level of the state, as occurs in the oil industry. This makes game theory a powerful tool to explain the market dynamics of large mineral resources such as oil, especially when combined with economic data and analysis. In our case, the economic data are best summarized by the cost curve for global oil production.

The Cost Curve

The cost curve goes back at least two hundred years to Ricardo. The explanatory note below illustrates how the cost and demand curves interact to set the price and produced volume, or quantity, of a particular commodity product.

By way of an example, consider a village in an ancient era of agricultural economics. A number of landowners own the arable land around the village. Their fields are of varying size and quality. In some, wheat grows effortlessly. In others, it takes a lot of work for more meager harvests. Yet the needs the population and the demand for wheat require development of the less fertile lands that produce less per acre for the same amount of labor.

Now let's sort the fields in descending order of fertility, with $Q_1, \ldots, Q_n$ *being the amount of wheat that each can produce. Let's also denote* $c_1 < \ldots < c_n$ *as being the cost of producing a bushel of wheat in each of the fields. The cost curve for the village can be represented graphically as shown below. We can also add a demand curve—shown in red—but note that its slope is opposite to that of the cost curve. The point of intersection of the cost and demand curves gives the price* $p^* = c_k$, *with* $k = 3$ *in our example for which supply and demand are balanced with* Q^* *bushels produced.*

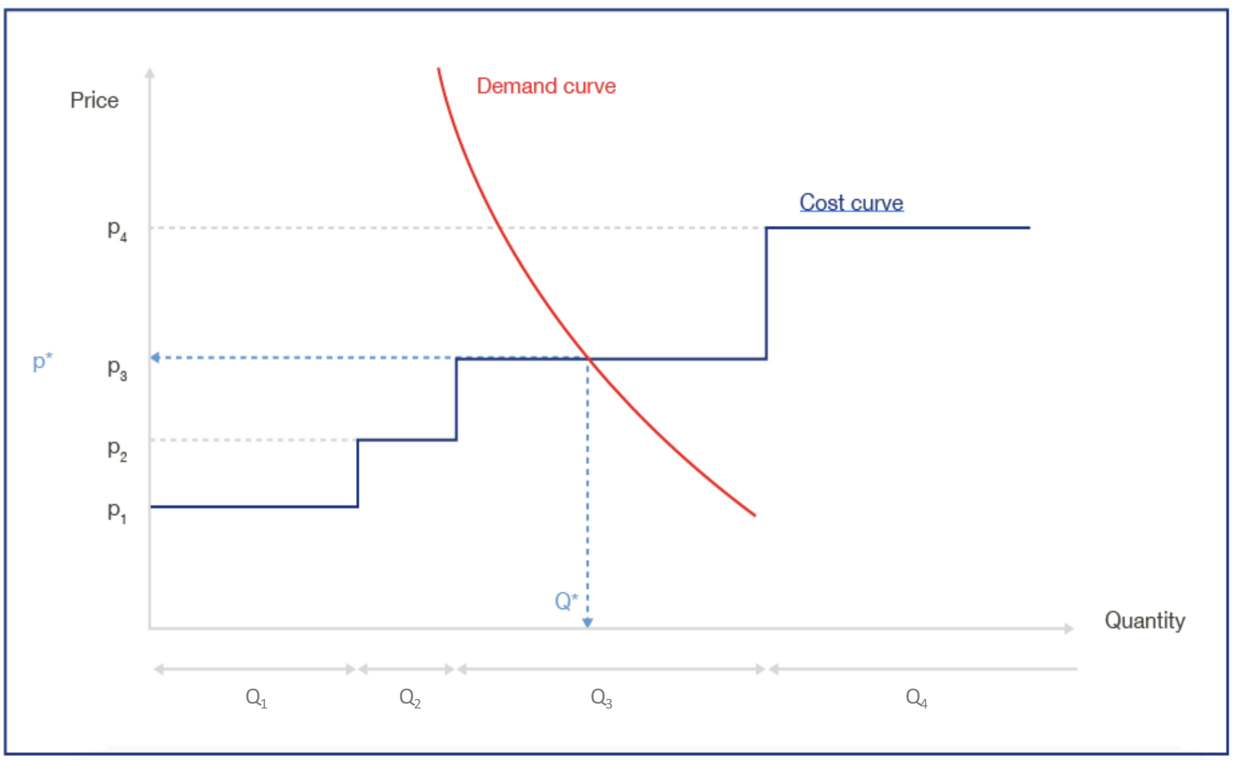

Figure 1: Cost and Demand Curves for Wheat Production in an Ancient Economy

Among the landowners, there will be some (namely k, ..., n) who will leave their fields fallow as the quantity of wheat they produce will not cover the cost of production. Others, (namely 1, ..., k-1), who exploit the most fertile lands, will receive rent that results from the difference between the cost of production, c_i, on their land, and the cost of production, c_k, on the least fertile land being exploited. The rent also depends on the landowners' capacity to produce, and is equal to $(c_k-c_i)Q_i$. This term represents the Ricardian differential rent. Such rents have long been decried by economists because they result from the simple right of ownership without any value being added by the owner.

The cost curve of the oil industry is well known (see Figure 2 below). We will use it and look both at the theory of non-cooperative games, and at the theory of cooperative games, before looking closely at the combination of cooperative and non-cooperative behavior to explain the past behavior of OPEC and predict the organization's potential future moves.

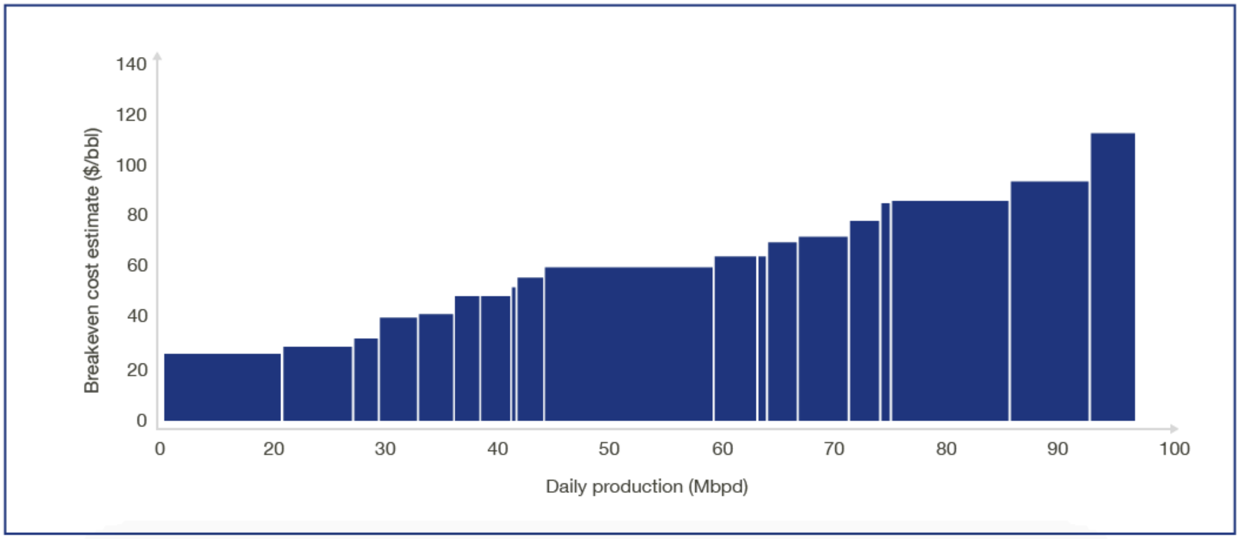

Figure 2: Cost Curve for Worldwide Oil Production. Source: Kayrros, EIA

The Theory of Non-Cooperative Games and Nash Equilibria

To understand what the theory of non-cooperative games has to say, or not say, about the behavior of the world's oil producers, consider the fictitious examples in the note below.

For the sake of simplicity, let's assume that the global demand for oil of 100, equal to 100 MMbpd for example, is not price elastic. Let's also suppose there are two producers, A and B. Producer A produces with a constant cost of 10 per unit. Producer B produces with a constant cost of 30 per unit. Each could satisfy total demand alone. The best strategy for Producer A is to produce 99 units. He then lets Producer B produce the remaining unit and the market price will be slightly above 30 in order to let Producer B make a small profit. Producer A's profit will be 99 times 20.

Now suppose Producer A1 enters the market. Producers A and A1 both produce with a constant cost of 10 per unit while Producer B produces with a constant cost of 30 per unit. As before, either Producer A or Producer A1 alone can satisfy total demand.

In this case there are many Nash equilibria. For example, Producers A and A1 could produce 27 and 72 units respectively to make a total of 99 units. They would then allow Producer B to produce 1 unit, and the market price will again be slightly above 30 per unit. In this case, Producers A and A1 make profits of 27x20 and 72x20 respectively. But A has no interest in producing more. Indeed, if A were to produce 28 (and A1 continue to produce 72), prices would collapse to 10 per unit since B, which would be out of the market by then, is no longer there to dictate a price above 30.

In other words (27,72,1) is a Nash equilibrium. Neither of the three producers have any interest in changing their level of production if the others do not do so. In the absence of any cooperation, a Nash equilibrium is likely to continue. In this example, any distribution of output (a, a1) such that a+a1=99 (and b=1) is a Nash equilibrium. The profit of A is 20a, and that of A1 is 20a1. Producers A and A1 share a total profit of 20x99. The interests of the two producers are therefore completely opposite and there is no possible cooperation.

Let's now suppose that there are ten producers. Producers A1, ..., A9 all produce with constant cost equal to 10 per unit. Producer B produces with constant cost equal to 30 per unit. There are also an infinitive number of Nash equilibria in this case. In exactly the same way as for our three Producers A, A', and B, any distribution of the total production of 99 units between Producers A1 to A9 while Producer B produces 1 unit represents a Nash equilibrium.

We see from this that there is no interest in cooperation among the producers because their interests are very much opposed. In the real world, if there are several Nash equilibria, which one is adopted by the producers?

There is no answer to this question from the theory of non-cooperative games. So to find at least a partial answer to this question, we must broaden our point of view by turning to the theory of cooperative games.

The Theory of Cooperative Games and the Need for an Arbitrator

As we have said, the issue of the strategic behavior of a group of producers is complex. In the examples we have just examined, the producers have no interest in cooperating. Now let's look at some examples where cooperation can bring something of interest to the producers.

First, suppose there are now three main producers A, B, and C as well as a few small competitors on the fringe. The demand for oil remains unchanged at 100 units, and there is again no elasticity to price. The production costs of Producers A, B, and C are 10, 20, and 30 respectively. On the fringe, the cost of production is also constant and is equal to 50. Each of the Producers A, B, and C can produce a total of 40 units.

Now consider a distribution of production (a, b, c) between the Producers. If the sum of a, b, and c were to be 99, and if a, b, and c are all less than 40, then the competitive fringe will produce 1 unit, the equilibrium price will be 50, and Producers A, B, and C will make profits of 40a, 30b, and 20c respectively. As before, this is a Nash equilibrium with none of the producers having any interest in changing their level of production as long as the others do not do so either.

However, and contrary to the earlier examples from non-cooperative game theory, the interests of the producers are not completely opposed. There is room for cooperation and coalition.

Suppose, for example, that the initial production distribution is a=23, b=32, and c=44. The profits of Producers A, B, and C are therefore 23x40, 32x30, and 44x20 respectively. But now Producers A and B agree on a new production distribution with A producing 40 units and B producing 15. The total production of Producers A and B remains unchanged at 55 units. Between them, Producers A and B will make an overall profit of 40x40 + 15x30 equal to 2,050, a figure that is higher than their previous profit of 1,880 or (23x40 + 32x30). However, Producers A and B must now agree on how to share the total profit. In doing this, Producer A will have to receive more than 23x40, and Producer B more than 32x30 for everyone to accept this new distribution of production and profit. One solution might be 1,000 for A, and 1,050 for B. But this is not the only solution and there is now a need for negotiation, even if the producers are interested in finding some common ground.

Other negotiation arrangements are possible. For example, Producers A and C could negotiate without Producer B, or Producers B and C could talk to the exclusion of Producer A.

A three-way negotiation might also take place, which, if it succeeds, would maximize profits for all three producers. Producer A, for example, could produce 40 units, B 40, and C 19. The total profit would now amount to 40x40 + 40x30 + 19x20, equal to 3,180. However, Producers A, B, and C must agree on how to share the profit and they must also have confidence in the agreement that they have made. This would require another body to be the depositary of the contract and the guarantor of its execution.

The theory of cooperative games leads to the necessity of having an arbitrator asthe depositary of the contract and the guarantor of its execution. This last point is extremely important. It is potentially very difficult to achieve in the real world as it would be impossible to find a third party trusted and able to ensure that the partnership agreement would be respected over what would be a very long period.

There are in fact at least two conditions for a partnership, or coalition, to be formed and to function.

First, there must be a formal record that details who does what, and who receives what in the sharing of any gains. Second, all members of the coalition must be certain that the partnership contract will be respected by all. In the multinational world of oil production, it is clear that the ability to enforce agreements of this type is somewhat limited.

For example, no producing country would agree to give up its oil industry by selling its market share to a producer in another country in exchange for a promise from that country to share its profits over the long term even if those profits were to be higher than the first country could achieve on its own. One reason for this is the

variety of geopolitical risks that would cast doubt on the durability of any promise despite the credibility, sincerity, and commitment of its parties.

We must therefore find another angle to our strategic and economic analysis in which geopolitical risks and forces play their real-world roles, taking into account only the credible commitments that can be made in our search for cooperative solutions. To do this, we will now focus our analysis on the stable and sustainable coalitions that can be formed given the economic and geopolitical issues of today.

Optimum Size of the Coalition

We have seen that it is difficult to conceive of many coalitions given the geopolitical nature of oil. So, let's go in the opposite direction and suppose that there could be a single coalition. What can game theory tell us about the size of such a coalition?

Let's start by assuming that the coalition will behave like a monopoly faced with a competitive fringe formed by the producers that do not join the coalition. The coalition will choose the production level Q that maximizes its profit, taking into account the reaction of its competitors. The n members of the coalition will establish production quotas among themselves, $Q_1, \ldots, Q_n$ with ($Q = Q_1 + \cdots + Q_n$), so that their overall profit is maximized within a competitive context.

Suppose that global demand D(p) is given, in MMbpd, by D(p)=100-p/30 where p is the price per barrel. This is an idealization of course, but one which is still relatively realistic. Indeed, with this demand function, at a price of \$60/bbl, the global demand for oil is 98 MMbpd. At \$120/bbl, demand drops only slightly to 96 MMbpd.

Now suppose that the cost curve of the competitive fringe is given by $C_F(q)=2q-50$. This again is an idealization, but again relatively realistic. Indeed, with this cost curve, if production of the competitive fringe was 40 MMbpd, then the marginal cost per barrel, meaning the cost of the most expensive producer, would be \$30. If production of the competitive fringe was 60 MMbpd, then the marginal cost would be \$70 per barrel.

Let's further suppose that the coalition's cost curve is given by $C_M(Q)=Q-20$, once again an idealization of reality but once again realistic. With this cost curve, if the coalition production was 30 MMbpd, the marginal cost would be \$10/bbl, and if the coalition's output was 60 MMbpd, the marginal cost would be \$40 /bbl. In other words, the cost curve of the coalition is lower than that of the competitive fringe, and its slope is half as steep.

In this context, if the coalition decides to produce a total quantity of Q, the equilibrium price p and the equilibrium production of the competitive fringe will be such that supply and demand are equal and that the marginal cost of coalition production and of the competitive fringe are also equal.

In other words, $Q + q = D(p)$, *and* $C_F(q) = p$

From this we get $Q + q = 100 - p/30$ *and* $2q - 50 = p$

Leading to $Q + (50 + p)/2 = 100 - p/30,\ p/2 + p/30 = 75 - Q$, *and* $p = \frac{30}{16}(75 - Q)$

If the coalition now chooses Q in order to maximize its profit P with:

$$P = \left(p - C_M(Q)\right)Q = \left(\frac{30}{16}(75 - Q) - (Q - 20)\right)Q$$

Then:

$P = (160.6 - 2.875Q)$

From the above, we find that the level Q* of production of the coalition which maximizes its profit is Q*=160.6/(2x2.875)=28 MMbpd. The result of this calculation considers a global demand of around 100 MMbpd.

Mathematically, the profit $P = (a - bQ)Q$ is a quadratic concave function which reaches its maximum where its derivative a-2bQ is zero.

It is important to note that if we change the cost curves C_M and C_F while remaining realistic in orders of magnitude, then we always find that Q* is close to 30. A second numerical example that demonstrates this is shown in the appendix to this episode of the Oil Games.

The stability of the optimal quantity for the coalition is stable regardless of how many producers are in the coalition. If a competition producer wishes to leave the fringe and join the coalition, the optimal production of the coalition will not change and remain at around 30 MMbpd. As a consequence, it will be necessary for existing coalition members to restrict their production so as to leave room for a quota to be set for the newcomer. It will also be necessary for the newcomer to accept the production restrictions that the coalition imposes on its members.

For the coalition to be effective, it must group those countries whose individual cost curves are similarly low and not very steep. For if such countries were to be outside the coalition, they would produce significant quantities of oil at low cost to seriously reduce the coalition's capability to realize the profit from what is effectively a semi-monopoly. Once a coalition has been formed between those countries whose cost curves are low and not very steep, there is no need to increase the number of member countries because the optimal overall production level of the coalition does not vary much with the arrival of a new member, and because the newcomers would restrict production and lower the profit of all the existing members.

Stability of OPEC Market Share

Our calculations have allowed us to highlight that according to this model, OPEC’s optimal production should be around 30 MMbpd. If we were to increase global supply and demand by 10%, then the figure of 30 MMbpd would need to increase to 33. In other words, the calculations we have made are market share calculations. Hence according to this model, the optimal OPEC market share, defined as the market share that maximizes OPEC’s profit, should stay constant at around 30%.

If we now look at the past few decades, we can see that OPEC market share remains within a fairly narrow range around its current level. This is almost as if an invisible market hand has been guiding OPEC to gradually increase its capacity to attain the market share that maximizes its profit, which is constant according to the above model. Put another way, this implies that OPEC do not target a price but adjusts its production volume to maximize its profit while leveraging high-cost production from the non-OPEC members for maximum benefit.

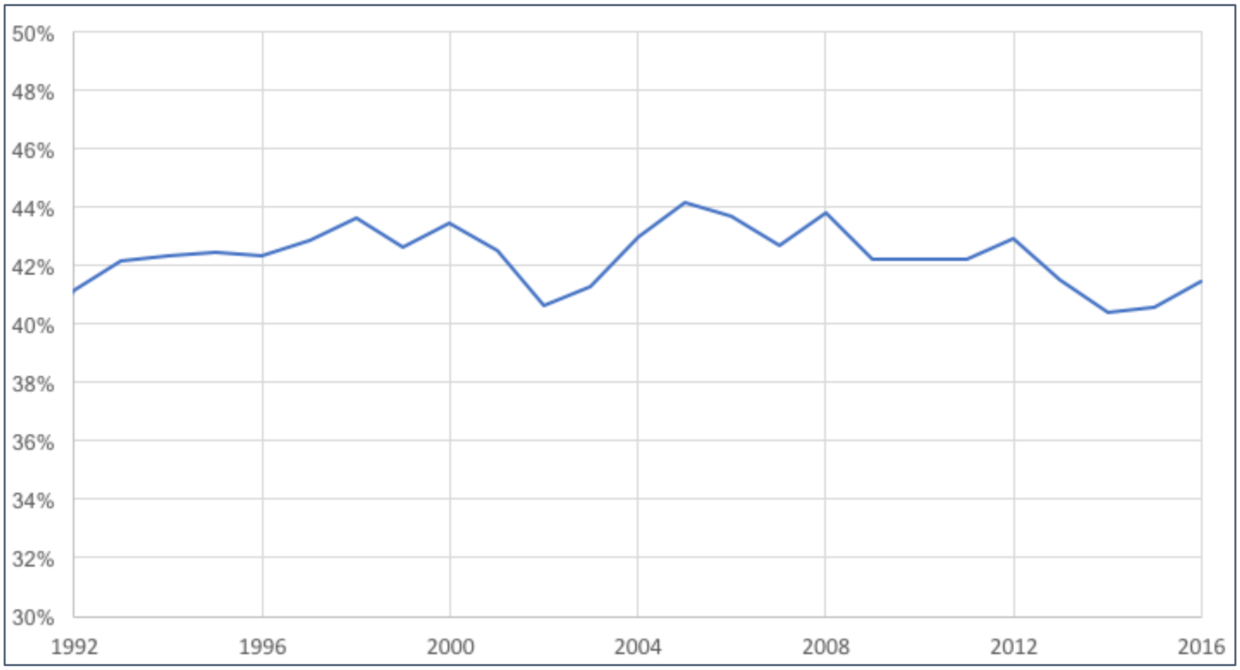

Figure 3: OPEC Crude and Condensate Market Share since 1992. Source: EIA

We can see that from 1992 until today the market share of OPEC has been relatively stable while demand and production have changed significantly. The stability shown agrees with our previous reasoning.

However, the market share of OPEC oscillates within a small range of between 40 and 44%, with an average of 42%. This is higher than we might expect, with our calculations indicating a figure more of the order of 30%. **The reason for this 12% gap will be explained when we come to look at dynamic modeling in a later episode of the Oil Games.** Dynamic modeling will also explain the oscillations around 42%, and will show more clearly the invisible hand that channels self-interested and group strategies to yield small and slow oscillations in market share.

In the future, OPEC might want to explicitly set some rules in adjusting its production to world demand in order to maintain its optimal market share.

If we were to think only about changes in oil demand, the adjustment rules might for example be a half-yearly adjustment in which the next six months' production is based on the past six months' production—increased or decreased by a combination of the difference between the targeted market share and last six months' market share as well as the difference between the five-year average of global stock levels and the stock levels of the past six months. **This would be a way for OPEC to continue to maximize its profit by maintaining its market share, and adjusting to changes in demand while taking inventory levels into account through an explicit strategy.**

But OPEC also has to manage other strategic issues. These include its own membership, with new members joining, or old ones leaving. New members might have lower costs, or incentives to accept production quotas. Russia would be an example. In addition, the recent burst in growth of US shale oil production represents another issue to be managed.

Will Shale Disturb OPEC Market Share Stability?

Episode 3 of the Oil Games has shown us how game theory can help us understand the balance between OPEC and the rest of the world's producers. It has shown the need for an arbitrator such as OPEC, it has explained why OPEC market share is so stable, and it has given us a formula for future OPEC-NOPEC deals.

It has not, however, dealt with the effect of the rapid rise of shale oil production, nor has it explained the gap between the market share predicted for OPEC by game theory, and that actually achieved.

In the next episode of the Oil Games, we will introduce dynamic modeling to explain why OPEC market share has been remained around 42% as well as how much market could be taken by the shale oil Players in the longer run.

Appendix

Here is a second numerical example to verify that the optimal quantity for the coalition depends very little on the cost curve provided that we remain in the field of the curves that correspond in first approximation to the current effective context.

Suppose that the global demand D(p) is again given (in MMbpd) by D(p) = p-100/30 and suppose that the cost curve of the competitive fringe is given by $C_F(q) = 3q-90$.

Once more this is an idealization of reality, but it is still relatively realistic. Indeed, with this cost curve, if the production of the competitive fringe was 40 MMbpd, then the marginal cost—meaning the cost of the most expensive producer—would be $30. And if the production of the competitive fringe was 60 MMbpd, then the marginal cost would be $90.

Suppose now that the coalition's cost curve is given by $C_M(Q) = Q/2$. *Yet again this is an idealization of reality but remains relatively realistic. Indeed, with this cost curve if the production of the coalition was 30 MMbpd then the marginal cost would be $15; and if the coalition's output was 60 MMbpd the marginal cost would be $30.*

In other words, the cost curve of the coalition is lower than that of the competitive fringe and its slope is six times smaller.

In this context, if the coalition decides to produce a total quantity Q, the equilibrium price p and the equilibrium production of the competitive fringe will be such that supply and demand are equal with Q+q = D(p), and that the marginal cost of the competitive fringe and the market price are also equal with $C_F(q) = p$.

Hence: $Q + q = 100 - p/30$ *and* $3q - 90 = p$

From which: $Q + (90 + p)/3 = 100 - p/30$, $p/3 + p/30 = 70 - Q$, *and* $p = \frac{30}{11}(70 - Q)$

The coalition chooses Q to maximize its profit P with $P = \left(p - C_M(Q)\right)Q = \left(\frac{30}{11}(70 - Q) - \frac{Q}{2}\right)$

From which $P = (191 - 3.22Q)Q$

And from where we find that the level Q of production that maximizes profit is Q*= (191)/(2x3.22), equal to 29.6 MMbpd.*