Enduring Feedback Structure and Long-Term Futures for the Upstream Oil Industry

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June 2016

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1 The author is grateful to two anonymous referees and to the editors for their perceptive criticism and helpful suggestions.

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Abstract

A fundamental idea in system dynamics is that interdependencies in business and society significantly influence the performance over time of firms and industries. This idea is often summarised in the phrase 'feedback structure gives rise to dynamic behaviour'. But what if the time horizon of a modelling study spans decades, as is often the case in models of natural resource management? Is it possible to find enduring feedback structures that shape events over such long periods? An example is presented based on a well-known system dynamics model of the upstream oil industry. The model was originally developed in the late 1980s and subsequently updated. The model's structure is reviewed against the backdrop of recent expansion in U.S. shale oil production. Shale oil is undoubtedly a major technology breakthrough in oil recovery. However this change pales in significance, when seen against the backdrop of strong and enduring feedback processes that coordinate OPEC production. Simulations show that OPEC retains the power to control oil price, dominate global production and drive commercial producers (including frackers) out of the industry. Further simulations test the so-called 'Saudi America' hypothesis and reveal that US frackers could not plausibly displace Saudi Arabia as the oil industry's swing producer.

Keywords: upstream oil industry, investment policy, feedback structure, long-term dynamics, sustainability

Introduction

In a fast-changing world one might think it is foolhardy to develop models that look far into the future and assume the character of business enterprise and industrial society somehow remains the same. Yet that is precisely what modellers do, particularly when dealing with topics such as resource management and sustainability. The time horizon for studies of global sustainability in *World Dynamics* (Forrester 1971) and *Limits to Growth* (Meadows et al 1972 and 2002) was two centuries. Models of fishery dynamics with surprise population collapse typically span decades. The petroleum lifecycle model

(Sterman and Richardson 1985; Davidsen et al 1990) foresees peak oil within the next century.

In this paper I use the oil producers' model (Morecroft and van der Heijden 1992) to show the power and influence of enduring feedback structure amid rapid and unforeseen technological change. The model was first developed in the late 1980s and updated in the mid-1990s. It was then updated again in 2014 to accommodate the rise of shale oil. The time horizon of the original study was 25 years. Since then hydraulic fracturing (fracking) has made possible the recovery of vast reserves of shale oil that were previously deemed inaccessible.

My analysis argues that while the 'shale gale' is important it must be seen against the backdrop of enduring feedback structure among the OPEC nations that coordinates OPEC's production. I first present the history of oil price and the original feedback structure of the industry devised in consultation with industry experts. This material is based on edited excerpts from Chapter 8 of *Strategic Modelling and Business Dynamics* (2nd edition) 'Industry Dynamics – Oil Price and the Global Oil Producers', Morecroft 2015. I then go further to consider the advent of shale oil and the extent to which this technology breakthrough has changed the structure of the original model and the industry. The answer is not much.

I then go on to selected simulations that show the possible effects of shale oil on long-term dynamics of oil supply and oil price. Since the model's feedback structure is not radically altered then its repertoire of long-term dynamics remains similar to those exhibited in the original model. Simulations show that OPEC retains the power to control oil price, dominate global production and drive commercial producers (including frackers) out of the industry. These results are in marked contrast to the views of some industry experts who have argued that fracking will transform the industry beyond recognition, undermining the power of OPEC. Such pundits even envisage the US replacing Saudi Arabia as the industry swing producer control of the global oil market and oil price (*The Economist* 2014).

Long-Term Oil Price Dynamics

The long-term behaviour of oil price reveals striking contrasts between periods of price stability, mild price fluctuations, dramatic price surges and equally dramatic collapses. Figure 1 shows world oil price spanning 142 years, from 1869 to 2011; a remarkably long time series. The vertical axis is on a scale from zero to 100 dollars per barrel in 2010 dollars. The inset updates the time series to 2017. Lying behind these price trajectories is the turbulent history of the oil industry as vividly told in *The Prize: The Epic Quest for Oil Money and Power* (Yergin, 1991) and *The Quest: Energy, Security and the Remaking of the Modern World* (Yergin 2011).

Between 1869 and 1880 there was extreme price volatility. This period corresponds to the early pioneering days of the oil industry in the Pennsylvania Oil Regions of the United States. The chaotic mix of speculators, fortune-seeking prospectors and their greedy exploitation of newly discovered reserves led to extraordinary periods of overproduction – too many wells and too much oil. The price trajectory in Figure 1 gyrates wildly, starting at $58 per barrel in 1869, rising to $75 per barrel by 1872, and falling to only $20 per barrel in 1874. Over the next two years to 1876, the price rose sharply to $50 per barrel before falling again to $18 in 1879. Then followed an interval of relatively low and stable oil price in the decade to 1889.

<u>Figure 1 here</u>

This shift to stability was imposed on the industry through the vision and will of John D. Rockefeller, founder of Standard Oil. His objective was to end what he described as a cut-throat policy of making no profits and instead make the oil business safe and profitable – by controlling supply and especially refining and distribution. The long-term results of Rockefeller’s efforts are evident in the relative calm between 1889 and 1939, when the price moved in a range between $10 and $25 per barrel. There is some evidence of a short-term price cycle with an interval of about four years from peak to peak. Nevertheless, there is much greater price stability than in the pioneering early days.

Rockefeller's era of supply discipline, ruthlessly imposed on a naturally chaotic industry and its fledgling markets, led to the rise of the integrated oil company and the enduring legacy of the 'Seven Sisters'. (The Seven Sisters is a term credited to Italian Enrico Mattei to describe the close association of the major oil companies: the four Aramco partners – Jersey (Exxon), Socony-Vacuum (Mobil), Standard of California and Texaco, together with Gulf, Royal Dutch/Shell and British Petroleum.)

In the post-war era from 1945 to 1970, this legacy and stable industry structure remained in place – almost unchallenged – even as the Seven Sisters expanded their operations internationally on the back of colossal oil reserves in the Arabian Peninsula. Despite these huge reserves, and the rapid expansion of oil output in the post-war era, prices were remarkably stable as Figure 1 shows. The price tranquillity was a far cry from the chaos of the Pennsylvania Oil Regions at the birth of the industry. Throughout this era, which spanned two and a half decades, supply and demand were in almost perfect balance – an astonishing achievement when one considers the complexity of the industry, its global reach, the diversity of stakeholders (encompassing producers, consumers and nations), and the array of objectives sought by these stakeholders from their share in the oil bonanza.

Already, however, new forces were at work, stronger even than the Seven Sisters, ushering in a new era of oil supply politics. As the locus of production moved to the Middle East, so the global political power of the region was awakened, feeding on western industrial countries' appetite for Arabian oil to sustain energy-intensive economies and lifestyles. Control over Middle Eastern oil was seized by the newly-formed OPEC – the Organisation of Petroleum Exporting Countries. In 1974, and again in 1978, OPEC exercised its power by withholding production and forcing up the price of oil. As Figure 1 shows, the price doubled and continued to rise to a peak of more than 70 dollars per barrel by 1979 – a peak not seen since the early days of the Pennsylvania Oil Regions. Hence, in the 1970s, after two decades of managed calm and predictability, chaos returned to global oil markets.

After 1979, price fell sharply to only \$20 per barrel by the mid-1980s. For almost 20 years price fluctuated in the range \$15 to \$30 per barrel, but there were no further upheavals to match the dramatic variations of the 1970s. As the turn of the century approached, oil price was still low. In fact, many industry observers at the time believed it would remain low for the foreseeable future. However, the industry proved them wrong. Price began to rise again in 2001, reaching more than $30 per barrel by 2004 and $90 per barrel in 2009. By 2013 price had risen to more than $100 per barrel. Yet as 2014 drew to a close press reports began to appear suggesting that a new era of lower price, below $80 per barrel, may be dawning. The inset to Figure 1 shows how things turned out with oil price falling well below $60 per barrel from 2015 to 2017.

The Upstream Oil Industry and Market Forces

A 'systemic' explanation of price behaviour lies in the feedback processes that balance supply and demand in the global oil markets. Periods of price stability correspond to times in which supply and demand are more or less in balance. Price spikes in the 1860s and 1970s correspond to times in which demand greatly exceeded supply. The gentle price roller-coaster of the early 1900s corresponds to a period in which supply sometimes exceeds and sometimes falls short of demand, but never by much. The remarkable price stability of the 1960s corresponds to a golden age of perfect supply management.

A useful template to begin conceptualisation of the oil industry is a balancing loop with delay that depicts commercial market forces of supply and demand, as shown in Figure 2.

<u>Figure 2 here</u>

If demand for oil exceeds production then the resulting production shortfall leads to an increase in market oil price. Higher price improves profitability (shown as the price to cost ratio) which leads to an increase in capacity approval and additional capacity in construction. Eventually, after a construction delay, both capacity and production increase to eliminate the production shortfall.

However, such a simple feedback loop by itself cannot explain the sustained price stability of the 1960s and 1970s. The corrective mechanism of capital investment, with its construction delay of almost five years, is simply not responsive enough to guarantee the near perfect balance of supply and demand that price stability requires. Equally, the invisible hand of balancing feedback alone cannot explain the wild price gyrations of the 1860s and 1870s, or the memorable price hikes of the 1970s and early 2010s. Reasoned commercial investment decisions should not result in oil famines and feasts with such extreme price movements. Obviously there are other feedback processes at work in the global oil system. Some must be fast-acting to prevent temporary imbalances and to short-circuit the inevitable time lags of commercial investment. Others must work to sustain imbalances, yet be powerful enough to override the natural balancing tendency of market forces and the invisible hand.

Model Development Process

To gain more insight into the structure of the industry a project team from Royal Dutch/Shell (10 people in all) came together to share their knowledge about oil companies, oil producing nations and motives for investment and production[2]. Figure 3 shows the resulting overview of global oil producers comprising five main sectors. On the right are the independent producers making commercial investment decisions in response to the needs of the market and oil consumers. On the left are the swing producer and the opportunists that make up the oil producers' organisation OPEC. This powerful group of producers has access to very large reserves of low-cost oil. Their production decisions are motivated principally by political and social pressures, in contrast to the commercial logic of the independents. They coordinate production through quota setting. The opportunists agree to abide by quota, but will sometimes cheat by producing above quota in order to secure more oil revenues. The combined output of all three producer groups supplies the market where both price and demand are set. Price itself responds to imbalances in supply and demand and then feeds back to influence both demand and the behaviour of producers.

Figure 3 here

2 The original model development took place in 1988-89 as an input to Shell's scenario planning at the time (Morecroft and van der Heijden 1992). It was updated in 1996 to include the effect of vast reserves from the opening-up of Russian oil fields after the fall of Communism. The model was updated again in 2014 to take account of new reserves from the exploitation of shale oil in the US.

Now consider, in broad terms, how these five sectors are linked. In a purely commercial oil world there are only two sectors: the independents and the market. The market establishes the oil price and also consumers' demand for oil at the prevailing price. The oil price drives independents' investment and, eventually, leads to a change in production, which then feeds back to the market. The closed loop connecting the two sectors is none other than the balancing loop with delay mentioned earlier.

OPEC's involvement begins with quota setting. The nations of OPEC must collectively decide on an appropriate production quota. They do this by monitoring oil demand from the market and subtracting their estimate of independents' production. This difference is known as the call on OPEC and is the benchmark relative to which overall quota is set. The agreed quota is then allocated among member states. A portion called the swing quota goes to the swing producer and the rest to the opportunists. If OPEC is unified then all members follow quota, with the exception of the swing producer who makes tactical adjustments to production to ensure that oil price remains close to OPEC's target. Production from both the swing producer and opportunists then feeds back to the market, thereby completing the supply loop. As we shall see later there is additional detail within each sector. For now, however, there is enough: five interconnected sectors to begin representing the rich and complex feedback structure of the global oil industry.

A Closer Look at the Stakeholders and Their Investment/Production Decision Making

To uncover the operating detail behind this feedback structure of the oil industry the modeller led a discussion among the Shell team about the investment and production decision making of each main producer group. The standard behavioural formulation principles of system dynamics helped to frame the discussion and to identify the dominant logic of investment decisions and the information flows on which they depend[3]. For example, what do executives in commercial oil companies know and pay attention to as

[3] The formulation principles include the so-called 'Baker criterion' and recognition of bounded rationality in decisionmaking that ensure fit to industry practice. For more details of these general formulation principles see Chapter 13 of *Business Dynamics* (Sterman 2000) and Chapter 7 of *Strategic Modelling and Business Dynamics* (Morecroft 2015).

they make their upstream investment decisions? What information really matters to OPEC oil ministers as they agree quotas and set production targets? Which organisational, social and political factors shape and filter the signals used by different producer groups and their leaders to justify investment and production decisions? The diagrams that follow are similar to the flip-chart drawings from team meetings in which all these questions, and more, were thoroughly explored as the basis for equation formulations[4].

Investment by the Independent Producers

The independents are all those producers – state-owned oil companies, the majors and other private producers – that are not part of OPEC and who expand crude oil output on the basis of commercial criteria. This category includes international oil companies such as BP Amoco, ExxonMobil and Shell, and non-OPEC nations such as Norway. The independents are assumed to produce at economic capacity all the time. Their production rate is therefore dictated by available capacity. The rationale for capacity expansion is dominated by commercial factors as shown in Figure 4. The circular symbol represents independent producers' upstream investment or capacity expansion policy – often known as 'capex'. The independents add new capacity when they judge it is profitable to do so.

The figure shows the main information inputs to upstream investment decisions used to calculate the average profitability of potential projects. Independents estimate the development costs of new fields and the expected future oil price over the lifetime of the field. Knowing future cost, oil price, the likely size of a new field and the tax regime, financial analysts can calculate the future profit stream and apply a hurdle rate to identify acceptable projects. In reality, each project undergoes a thorough and detailed screening, using well-tried upstream investment appraisal methods. The greater the estimated profitability, the more projects exceed the hurdle rate and the greater the recommended expansion of capacity. There is a scale effect too represented by information feedback from independents' capacity. The more capacity, the bigger are the independents and the more projects in their portfolio of investment opportunities.

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4 See Larsen and Morecroft (2006) for a full description of the equation formulations in the Oil Producers' Model.

<u>Figure 4 here</u>

Executive control of recommended expansion is exercised through capex investment optimism that captures collective investment bias among top management teams responsible for independents' investment. Optimism can be viewed on a scale from low to high. High optimism means that oil-company executives are bullish about the investment climate and approve more capacity expansion than financial criteria alone would suggest. Low optimism means executives are cautious and approve less expansion than recommended. It is important to appreciate the distance from which we are viewing investment appraisal and approval. We are not concerned with the detail of individual oil field projects. Rather, we are seeing investment in terms of commercial pressures that lead to fractional growth of existing capacity, where the growth rate is typically between 5 and 10 percent per year but can be up to 25 per cent per year when profitability is exceptionally high.

Quota Setting in OPEC

Quota setting takes place in two stages. First, OPEC members agree on a quota for the cartel as a whole. Then, member states negotiate individual quotas by allocating the total quota among themselves.

How much should OPEC produce? The main influences are shown in Figure 5. The cartel members need to form a view of the likely 'call on OPEC' over the time period covered by the quota agreement. To do this, they estimate both global oil demand and the independents' commercial production. The difference between these two quantities is the call on OPEC which is just a best guess of the volume of OPEC oil required to balance supply and demand. But the estimate need not be spot-on. In practice, it could differ from the actual call by as much as 1 or 2 million barrels per day. The swing producer will compensate for any mis-estimation by OPEC through swing changes to production.

More important than spot-on estimation of the call is for OPEC members to agree on whether to set an overall quota that is *deliberately* less than the estimated call, or deliberately more. By setting a quota that is less than the call, the member states are pursuing a policy aimed at increasing market prices. Their decision to over- or under-produce is politically and economically motivated and is represented by the scenario parameter ‘cartel quota bias’.

Figure 5 here

Quota negotiation allocates OPEC’s agreed quota among members. In reality, the negotiation is a highly political process, though a benchmark allocation is established based on objective criteria that include member states’ oil reserves, production capacity and population. In the model, quota is allocated in proportion to each member’s share of OPEC’s total operating capacity. Although this formulation is a simplification, it does capture the flavour of political bargaining by making the members’ bargaining strength proportional to capacity share.

Opportunists’ Capacity

The opportunists are all the other member states of OPEC besides the swing producer. The list of countries includes Algeria, Iran, Kuwait, Nigeria and Venezuela. Some of the opportunists are known to adhere strictly to quota, so their production policy is straightforward – it is simply equal to negotiated quota. Other countries, however, have a huge appetite for oil revenue to support their growing populations and developing economies. This need for revenue, coupled with underutilised production capacity, provides opportunists the motivation to exceed quota and to strengthen their quota negotiating position by deliberately over-expanding capacity.

Figure 6 shows the main influences on opportunists’ production capacity. Generally speaking, opportunists aim for surplus capacity, at least 2 or 3 per cent more than negotiated quota, partly to provide flexibility, but also to improve their bargaining position in future quota negotiations. The size of the surplus depends on a scenario parameter called capacity bias, which represents the tendency of opportunists to overbuild capacity.

Opportunists' change in capacity is formulated as an asset stock adjustment process where the effective target for capacity is equal to negotiated quota multiplied by the capacity bias.

Figure 6 here

Production of the Swing Producer

The role of the swing producer is to supply just enough oil to defend OPEC's intended price, known in the industry as the 'marker price'. A producer taking on this role must have *both the physical and economic capacity* to increase or decrease production quickly, by as much as 2 million barrels per day in a matter of weeks or months. This fast response is necessary to absorb unexpected variations in demand (due say to an unusually mild winter) or to compensate for surprise cuts in the output of other producers. The model makes the important assumption that the swing producer always has adequate capacity to meet any call. The project team felt this assumption was reasonable given the large capacity surplus of Saudi Arabia, estimated at 5 million barrels per day under normal supply conditions. A similar surplus remains today. As long as Saudi maintains this huge surplus then there is no need to model explicitly the capacity expansion policy of the swing producer, since capacity is never a constraint on output. Instead, the focus switches to the rationale for changes in crude oil production.

The swing producer (Saudi Arabia) operates in either swing mode or punitive mode. Most of the time Saudi is in swing mode, abiding by and supporting the production quotas set by OPEC. Occasionally, Saudi switches into punitive mode, by abandoning agreed quotas and rapidly cranking up production in order to discipline the other producers.

Figure 7 shows the factors influencing Saudi production policy when operating in normal swing mode. Production responds to pressure from both quota and oil price. There are two stock adjustment processes operating simultaneously. Saudi ministers change production in order to meet the swing producer's quota, but they also take corrective action whenever the market oil price deviates from the intended price that OPEC members collectively wish to achieve. When the price is too low, Saudi production is reduced below quota thereby undersupplying the market and pushing up the market price. Similarly, when the price is too high, Saudi production is increased above quota to oversupply the market and reduce price to the level OPEC is trying to defend. Such willingness to adjust production in the short term is in sharp contrast to the independent producers and is a defining characteristic of any swing producer.

Figure 7 here

In punitive mode, Saudi oil ministers feel that production is inadequate and they are not getting a fair share of the market. They decide to re-establish a strong position by increasing production regardless of the price consequences, thereby also punishing the other producers. The resulting punitive production policy is shown in Figure 8. The swing producer sets a minimum threshold for share of global demand (estimated to be 8 per cent) and will not tolerate anything less. Whenever market share falls below the threshold the volume of production is increased rapidly in order to flood the market with oil and quickly lower the price.

Figure 8 here

The team spent some time discussing the detail of punitive behaviour. For example, how does the swing producer decide on the volume of punitive production, and when do policymakers switch back to swing mode? The team's proposal was to include a punitive price, a low target price, for teaching a lesson to the other producers. Punitive production continues to expand until market oil price reaches the punitive price, or until the swing producer regains an acceptable market share (which is the signal to return to swing mode). The switch to punitive mode can send a powerful price signal to discipline the other producers. It is an act of last resort, however, because in this mode the swing producer has abandoned the role of price regulator – essentially the market is no longer managed.

Technology Change and The Rise of US Shale Oil

The existence of 'tight oil' reserves, trapped in oil-bearing shale rocks, has been known for centuries. Patented extraction processes date from the late 1600s and extraction industries became widespread during the 19th century. However, the industry shrank and virtually disappeared in the 20th century following the discovery of large reserves of cheaper and more easily extracted conventional oil. Tight oil was no longer commercially viable.

Recently the shale industry has staged a remarkable comeback through a combination of radical technology change and high oil price. Around 2008 specialist commercial oil producers began adapting the new technologies of hydraulic fracturing and horizontal drilling first used to tap shale gas. This technology breakthrough lowered the breakeven cost of tight oil below $70 per barrel, making it competitive with some of the more expensive conventional oil from offshore fields. As a result, between 2008 and 2013 shale oil production in the US rose swiftly from 0.5 to 3.5 million barrels per day, a 'shale gale' that surprised the industry and was entirely unforeseen in the original oil producers' project in the late 1980s..

One might argue that the model did not sufficiently endogenize technology change. But this view misses the key point that, despite the technology breakthrough, the vast majority of the model's feedback structure remains intact. The model is not principally about technology change but rather about competing and interlocking producer groups. The nature of their interaction has not changed. In particular the feedback processes that coordinate OPEC's production are the same today as they were in the late 1980s. Shale producers boost the supply of commercially viable oil but they do not and cannot change the dominant logic and political pressures governing the supply of oil from OPEC with its vast reserves of very low cost oil.

The emphasis given to technology change reflects model purpose, In the oil producers' model accessible reserves can increase as simulated time unfolds. The formulation is relatively simple. Technology is assumed to reduce the development cost per barrel <u>as a function of time</u> thereby shifting the cost curve downwards to enable more investment and production than would have been possible if technology had not improved.

To appreciate this modest role for technology in the oil producers' model consider the alternative approach taken in the petroleum lifecycle model (Sterman and Richardson 1985; Davidsen et al 1990). There technology depends endogenously on how oil firms set their budgets and allocate funds to technology development. The formulations fit a different purpose. The lifecycle model investigates the long-term economics of *profitable* oil production to shed light on phenomena such as 'peak oil', the energy transition and the evolving estimates of ultimate recoverable petroleum reserves. Investment decisions in exploration, production and technology are commercially motivated. There are no politically motivated producers in the model and there naturally comes a point in time when, even with advancing technology, it is no longer profitable to extract oil because the total (though unknown) initial quantity of oil-in-place is presumed to be finite and sooner-or-later there are viable substitutes.

In contrast the oil producers' model concerns itself with the repeating volatility of oil price seen in historical data for the upstream oil industry. The model finds an explanation of this volatility in the feedback structures that exist among and between competing producer groups, some commercially motivated with high-cost reserves (the independents) and some politically motivated with very low-cost reserves (OPEC members). This mix of producers can evoke prolonged periods of low oil price (as OPEC gains market share) punctuated by intervals of high price (as OPEC deliberately withholds production).

These differences mean that the models each display a distinct and limited repertoire of dynamics. For example the oil producer's model cannot explain peak oil or the energy transition because, over its limited 25 year horizon, it assumes that OPEC producers will *always* have plentiful supplies of low-cost oil. Indeed the model does not even contain the concept of ultimate recoverable petroleum reserves – only that the independent producers normally face rising development costs as *their* reserves are depleted. On the other hand the petroleum lifecycle model cannot explain huge gyrations in oil price such as those in the 1970s and more recently in the period between 2004 and 2016. Instead lifecycle simulations show oil price declining gently in the period between 1900 and 1950 and then rising in stages thereafter, punctuated only by short intervals of stable price.

This comparison illustrates that all models are wrong, but some are useful. The time horizons for the two models are radically different: 25 years for the oil producers' model and 200 years for the petroleum lifecycle model. These horizons belong with different dynamical processes and different reference modes. The oil producers' model does not ignore technological advances in oil recovery but instead places them in context of powerful low-cost OPEC producers. In this context it is the interplay of rival producer groups that drives oil supply and oil price.

What difference then might commercially abundant shale oil make to the performance of the global oil industry and to long-term oil price dynamics? The oil producers model was updated to investigate such questions, using publicly available information on reserves and production gleaned from the internet (BP Review 2014) and the business press. The revised model starts in 2010 at the end of a decade in which oil price had risen dramatically. This extended period of rising price unleashed the shale gale. Independents' undeveloped reserves are initialized in 2010 at 300 billion barrels of discovered oil, including shale reserves. A particularly significant change to the model is a boost to Independents' capacity made possible by shale oil. Capacity starts at 47 million barrels per day in 2010, more than 50 percent of global oil demand, and poised to grow still further as swathes of new commercial upstream capacity projects are approved and developed, many of them for shale oil. The initial growth rate of capacity is 4 percent per year, a rate destined to increase as swollen capacity in construction (26 million barrels per day in 2010) comes onstream[5].

[5] Note that all these updates to create the 2010 model are parameter changes to initial conditions. They do not change the feedback structure of the model.

A 2010-2034 Scenario: Subdued Global Oil Economy with Shale Gale and OPEC Supply Boost

By 2010 conditions in the oil industry had changed significantly by comparison with the mid 1990s. Global oil demand had surged to almost 90 million barrels per day in the wake of an Asian economic boom and oil price was more than $100 per barrel. Meanwhile Russia had become the world's biggest oil producer and output of shale oil was rising in the US[6].

Imagine now a scenario, starting in 2010, where the Asian boom has ended, global economic growth is moderate, and there is increasing environmental pressure to curtail the use of fossil fuels. The result is a subdued global oil economy[7] in which the world's appetite for oil is curbed. We also assume that shale oil is rapidly exploited[8] and that OPEC expands production through a combination of quota busting and deliberate oversupply[9]. Figure 9 shows a simulation of the scenario. The shale gale is evident in the trajectory for independents' capacity (line 1, top chart) which grows rapidly in the period between 2010 and 2016 from 47 million barrels per day to 63 million barrels per day; a huge increase of more than 30 percent. This expansion puts a severe squeeze on OPEC, forcing a decline in the cartel's agreed quota (line 1, bottom chart) from 41 million barrels per day in 2010 to only 34 million barrels per day in 2015. As a result the swing producers' production (line 3, top chart) falls by 50 percent between 2010 and 2013 while opportunists' production (line 2, top chart) remains level at 31 million barrels per day - despite opportunist's quota busting.

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6 These changes to global industry conditions are captured in 'Oil World 2010' along with the shale oil changes mentioned above..

7 A subdued global oil economy is achieved by setting to zero a parameter for the 'effect of global economy and environment on demand'. This setting means that for 25 years, from 2010 to 2034, there is no upward pressure whatsoever on oil demand, unless it comes from falling oil price.

8 A surge in shale oil production plays out through a variety of parameter assumptions that boost the capacity and output of the independents' sector. They include shale reserves, a high initial oil price, and an attractive commercial investment climate.

9 An OPEC supply boost is created by adjusting the parameters for 'cartel quota bias' and 'opportunists capacity bias'. Cartel quota bias is set to +0.05 . This change causes OPEC to deliberately oversupply the market by agreeing a collective quota for member states that is five percent higher than the call on OPEC. 'Opportunists capacity bias' is set to 0.1. This change activates quota busting within OPEC as individual member states attempt to boost vital oil exports and revenues.

Figure 9 here

The squeeze on OPEC invokes retaliation within the cartel. Starting in late 2013 the swing producer temporarily abandons the quota system and increases production far above quota in order to regain lost market share and to punish other producers for pumping too much oil. By early 2015 the swing producer's production (line 3, top chart) peaks at 17 million barrels per day. By comparison the swing quota peaks at only 9 million barrels per day (line 3, bottom chart). This surge of punitive production fails to quell the shale gale. Independents capacity (line1, top chart) remains above 60 million barrels per day from early 2014 to late 2017, reaching a peak of 63 million barrels per day in 2016 – one year later than the peak in swing production. The market is flooded with oil. Only the opportunists reduce production (line 2, top chart) from 30 million barrels per day in late 2013 to 25 million barrels per day in mid-2015. This modest reduction is too small to offset the supply glut.

After 2016, for the next two decades, the oil world changes almost beyond recognition. There is a gradual long-term decline of independents' capacity (line 1, top chart) from a peak value of 63 million barrels per day in 2016 to only 18 million barrels per day in 2034. The shale gale is over and conditions are now ripe for expansion of OPEC. The cartel's agreed quota (line 1, bottom chart) rises almost linearly from 34 million barrels per day in 2015 to 80 million barrels per day in 2030, partly to fill the supply gap left in the wake of the shale gale and partly as a result of sustained quota busting by opportunists overlaid on OPEC's deliberate policy of oversupply. Opportunists' quota (line 2, bottom chart) doubles from 25 million barrels per day in 2015 to 54 million barrels per day in 2034 while the swing quota (line 3, bottom chart) more than trebles in the same period.

If this future were to unfold the upstream businesses of big commercial producers like ExxonMobil and Shell would be reduced by two-thirds (just a shadow of their former selves) and the world would be more reliant than ever on oil from the Middle East.

How could such radical change happen? The answer lies in the geology and economics of the oil industry with its vast low-cost reserves concentrated mainly in the Middle East and its modest high cost reserves spread around the globe, trapped in awkward-to-reach places at the bottom of oceans, or in shale rocks and tar sands. If, as assumed in the 2010 scenario, global oil demand is subdued for more than two decades then OPEC may be tempted to compete on price and use its reserves to drive commercial producers out of business or at least curtail their market power.

Figure 10 shows the resulting demand and price trajectories. Demand (line 1, top chart) starts at 87 million barrels per day in 2010 and rises to 101 million barrels per day in 2017. Thereafter demand remains steady, hovering around 100 million barrels per day for the rest of the simulation out to 2034. An increase in demand may seem surprising given the scenario assumption of a subdued global-oil economy. However there is a glut of oil during the first seven years of the scenario which causes a rapid decline in market oil price (line 1, bottom chart). As oil price falls from $110 per barrel to less than $60 per barrel then oil consumption is stimulated, despite environmental pressure to use less fossil fuel.

Figure 10 here

Thought Experiment: A Test of the 'Saudi America' Hypothesis

The next simulation experiment tests an intriguing hypothesis advanced by some oil economists and reported in *The Economist* magazine (February 2014) that America will replace Saudi Arabia as the swing producer. Such a shift of power in the upstream oil industry would be highly significant if it were to happen and is therefore worth investigating with the simulator.

The hypothesis hinges on a belief that the short lifetime of tight oil wells in the US will enable shale oil producers to vary production sufficiently to control oil price. The reasoning is as follows. Oil flows sluggishly through impermeable shale rock by comparison with the much freer movement of oil through porous rocks that make up conventional reservoirs. As a result, the area that can be tapped with a shale well is much smaller than the area for a conventional well and, as pumping commences, production declines quite rapidly for the first few years (typically by 30 percent a year by comparison with only 6 percent a year for a conventional well). So when oil price rises, tight oil producers quickly drill more holes and ramp-up supply. When price falls they simply stop drilling and production soon declines. From this geological feature of shale rock arises the 'Saudi America' hypothesis that, if US shale production continues to expand, and the US becomes the world's largest oil producer, then America will acquire sufficient flexibility in oil production to replace Saudi Arabia as the swing producer.

To test the hypothesis the parameter called 'Average Lifetime of Field Wells' is reduced from 10 years to 5 years. Meanwhile OPEC is assumed to agree quotas just sufficient to meet, but not to exceed, the call on OPEC (the difference between global demand and independents' production). Note that a halving of the 'Average Lifetime of Field Wells' would require US frackers to be the dominant commercial producers. Whether or not such dominance is feasible is discussed later, but if it were then US frackers would become influential among global oil producers, just as the hypothesis assumes.

The results of the thought experiment are shown in Figure 11. There is a significant change in supply dynamics by comparison with the previous scenario. Independents' capacity (line 1, top chart) remains almost flat all the way to 2028 and only then begins to decline gradually. The distinctive capacity hump of the shale gale, clearly visible in Figure 9, has disappeared. Meanwhile swing producer production (line 3, top chart) closely matches the swing quota (line 3, bottom chart) meaning that Saudi Arabia no longer needs to exert supply control through bursts of punitive production. Moreover, the cartel's agreed quota (line 1, bottom chart) remains relatively stable for almost two decades, from 2010 to 2028, suggesting the cartel's influence on supply (or *need to influence* supply) is diminished, consistent with the 'Saudi America' hypothesis.

<u>Figure 11 here</u>

However, further simulations suggest the hypothesis is misleading. The US frackers are too small and fragmented to exert the stabilizing influence postulated in the hypothesis. The main reason is that just a small fraction of independents' overall capacity is in shale oil, which is anyway relatively expensive to develop. There is lots of conventional oil capacity too; in Russia's medium-cost oil fields, and in conventional deep-sea fields rendered profitable by high oil price. With all this commercially viable non-shale output already in the industry it is extremely unlikely that shale producers in the US can, by themselves, enforce production cuts big enough to stabilise price in the way the hypothesis suggests. It would take remarkable discipline by entrepreneurial frackers in the biggest US tight-oil production basins (such as Bakken and Eagle Ford) to withhold production for months on end, or even years, in the hope that oil price will rise. Meanwhile, conventional oil producers will continue to pump oil from their long-life wells, unable to match production cuts achievable in nimble tight-oil fields. Moreover, some shale oil producers will surely behave opportunistically, drilling new wells to sustain their output even as other shale producers cut back – rather like the opportunist producers in OPEC. So the most likely outcome for independents' output as a whole is a partial production cut, much shallower than imagined in the Saudi America hypothesis.

The true aggregate situation can be represented in the simulator by a smaller reduction in the average lifetime of field wells from (say) 10 years to 7 years (rather than 5 years). When this more realistic assumption is used then the main dynamic features of the original 2010 scenario reappear. The capacity hump of the shale gale returns, prompting bursts of punitive Saudi production that in turn causes a significant drop in oil price that US frackers are powerless to prevent. Of course it is important to bear in mind, as with all scenarios, that the trajectories are internally consistent stories, not accurate point predictions of future oil price and production. Nevertheless there is a strong message in the 2010 simulations. Unless there is another global economic boom, then we are entering an era of low oil price, ushered in by a shale gale that re-ignites the smoldering power of OPEC.

Conclusion

We know that profound and unforeseen political and technology changes have swept through the oil industry during our lifetimes. But the long-term future is not unknowable. There are enduring feedback structures within the industry that shape the unfolding future. These structures are found in the dominant logic of investment decisionmaking by different producer groups and in the pattern of the interlocking parts of the global upstream oil business. OPEC nations with their vast multi-decade reserves of low cost oil can continue to produce at oil prices far below those that are profitable for commercial producers. The advent of shale oil does not change this latent competitive advantage of OPEC. So the long term future of oil price is far more dependent on the coordination of production within OPEC than it is on technological advances in oil recovery. The paper has shown that the feedback structures governing OPEC output are enduring. They arise from the deeply embedded motives of a powerful swing producer (Saudi Arabia) and revenue-hungry producers in oil-rich developing nations.

Enduring feedback structures have been identified elsewhere in business and society besides the oil industry. Vivid and well-known examples are the structures underlying the long-term dynamics of growth, industrialization and decline in *World Dynamics* (Forrester 1971) and *Limits to Growth* (Meadows et al. 1972 and 2002). These dynamics span two hundred simulated years from 1900 to 2100. The models behind the two studies assume a deep-rooted and enduring tendency of an industrial society to inadvertently overinvest in capital while pursuing the beguiling objectives of growth in industrial output per capita and food per capita. These decisionmaking traits are embedded in a complex feedback setting that is recognisable as an industrial society complete with interlocking population, capital, natural resources and pollution. This growth-oriented system is capable of generating a surprise pollution crisis that results in collapse of the global system midway through the 21st century. A subsequent empirical study by Turner (2008) compares simulated data from the 'standard run' of *Limits to Growth* (which features a surprise pollution crisis) with 30 years of corresponding historical data from 1970 to 2000. There is a good match for variables such as global population, net birth rate, food per capita, industrial output per capita, non-renewable resources and pollution suggesting that the structures driving the simulated dynamics of the 'standard run' are indeed enduring, at least over a period of three decades.

References

BP Review (2014). *BP Statistical Review of World Energy*, http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html (accessed 14 October 2014).

Davidsen, P.I., Sterman, J.D. and Richardson, G.P. (1990). A petroleum life cycle model for the United States with endogenous technology, exploration, recovery and demand. *System Dynamics Review*,12(1), 1-19.

Forrester, J.W. (1971). *World Dynamics*. available from the System Dynamics Society www.systemdynamics.org originally published by Wright-Allen Press, Cambridge, MA.)

Larsen, E.R. and Morecroft, J.D.W. (2006) *Oil World 1988 Equation Description*, in the online learning support folder for Chapter 8 of the 2nd edition of *Strategic Modelling and Business Dynamics*, http://eu.wiley.com/WileyCDA/Section/id-825465.html (accessed 25 November 2016).

Meadows, D.H., Randers, J. & Meadows, D.L. (2002). *Limits to Growth: The 30 Year Update*. White River Junction, VT: Chelsea Green Publishing Company.

Meadows, D.H., Meadows, D.L., Behrens, W.W. III, *et al*. (1972). *Limits to Growth*. New York: Universe Books.

Morecroft, J.D.W. (2015). *Strategic Modelling and Business Dynamics,2nd Edition*, Wiley, Chichester UK.

Morecroft, J.D.W. and van der Heijden, KAJM (1992). Modelling the Oil Producers, in 'Modelling for Learning', special issue of *European Journal of Operational Research* , 59 (1), 102-12.

Sterman, J.D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston, MA: Irwin McGraw-Hill. (See, in particular, Chapter 13, Modeling Decision Making.)

Sterman, J.D. and Richardson , G.P. (1985). An experiment to evaluate methods for estimating fossil fuel resources. *Journal of Forecasting*, 4, 197-226.

The Economist (2014). The economics of shale oil: Saudi America. *The Economist,* February 15th 2014, 33-34. Also available from the online learning support folder for

Chapter 8 of the 2nd edition of *Strategic Modelling and Business Dynamics*, Wiley, Chichester UK. www.wiley.com/go/strategicmodelling2e (accessed September 2015).

Turner, G.M. (2008). A comparison of *The Limits to Growth* with 30 years of reality. *Global Environmental Change*, 18, 3, 397-411.

Yergin, D. (1991). *The Prize: The Epic Quest for Oil, Money and Power.* London: Simon and Schuster.

Yergin, D. (2011). *The Quest: Energy, Security and the Remaking of the Modern World.* London: Allen Lane.

Simulator and Interactive Learning Materials (including documented equation listing)

Morecroft JDW. 2015. Oil World 2010, in the online learning support folder for Chapter 8 of the 2nd edition of *Strategic Modelling and Business Dynamics*, Wiley, Chichester UK. www.wiley.com/go/strategicmodelling2e (accessed September 2015).