Background & Objectives

This journal addresses all aspects of the evolving Oil Age, including its physical, economic, social, political, financial and environmental characteristics.

Oil and gas are natural resources formed in the geological past and are subject to depletion. Increasing production during the *First Half* of the Oil Age fuelled rapid economic expansion, with human population rising seven-fold in parallel, with far-reaching economic and social consequences. The *Second Half* of the Oil Age now dawns.

This is seeing significant change in the type of hydrocarbon sources tapped, and will be marked at some point by declining overall supply. A debate rages as to the precise dates of peak oil and gas production by type of source, but what is more significant is the decline of these various hydrocarbons as their production peaks are passed.

In addition, demand for these fuels will be impacted by their price, by consumption trends, by technologies and societal adaptations that reduce or avoid their use, and by government-imposed taxes and other constraints directed at avoiding significant near-term climate change. The transition to the second half of the Oil Age thus threatens to be a time of significant tension, as societies adjust to the changing circumstances.

This journal presents the work of analysts, scientists and institutions addressing these topics. Content includes opinion pieces, peer-reviewed articles, summaries of data and data sources, relevant graphs and charts, book reviews, letters to the Editor, and corrigenda and errata.

If you wish to submit a manuscript, charts or a book review, in the first instance please send a short e-mail outlining the content to the Editor. Letters to the Editor, comments on articles, and corrections are welcome at any time.

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Editorial

Welcome to the Autumn 2016 issue of this journal. This time we carry only two papers, as follows:

The first is a review paper on the perceptions and realities of peak oil in China. This is an excellent paper, and exactly the type of review of the 'peak oil' topic within a country of which it is the intention to carry more in future.

Incidentally, in this paper readers' attention is drawn to its Figure 2, which I will term a 'CUP-B' plot, from its originating university. This gives, for different categories of oil, the size of estimated ultimately recoverable resource (URR), development cost, and upstream CO_2-equiv. emissions. (The authors of this plot note that it is derived by adding URR data to a plot of the type given by Figure 1 of Verbruggen and Al Marchohi, 2010; which in turn was based on Figure 3 of Brandt & Farrell, 2007). The significance of a 'CUP-B' plot is that - like Brandt and Farrell's Figure 3 - it shows on a single chart three key characteristics of any fossil energy resource (URR, cost and CO_2 emissions) which will be of increasing importance in modelling energy options in the future.

The second paper in this issue is quite long. It is the first part of a two-part paper that discusses data sources used in oil forecasting, and presents some of the problems with the data. This also is an important topic, as it can be argued that much of the confusion over past oil forecasts has resulted from the use of poor quality data; in particular on oil reserves, on apparent changes of these reserves over time, and on URR estimates by category of oil.

As the paper mentions, we intend to send copies to the organisations listed in the paper, to solicit corrections and criticisms. If useful feedback is obtained, then we intend to publish a corrected version in a future issue.

Note also that quite a number of the charts in this paper are complex, and may be difficult to read in black and white. It will be possible for subscribers of the printed edition to access a PDF version of the paper, giving the charts in colour, by contacting Noreen Dalton at: theoilage@gmail.com

I trust you find these papers of interest.

- R.W. Bentley, October 6th, 2016.

References

Verbruggen, A., and Al Marchohi, M. (2010). *Views on peak oil and its relation to climate change policy*. Energy Policy 38, 5572-5581.

Brandt, A.R., and Farrell, A.E. (2007). *Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources*. Climatic Change, 84:241-263.

The Debate and Reality of Peak Oil in China

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Abstract

China's oil consumption has been increasing significantly during the past decades while its oil production has been growing more slowly, making the gap between domestic oil supply and demand ever larger. Peak oil, now acknowledged by a number of nations, will become inextricably an issue for China, and is likely to impact China's national energy policy in the future. Currently debates on the peak oil issue are rare in China, and most senior Chinese officials, researchers and the general public do not recognise "peak oil" and its potential implications. This paper examines the current debate regarding peak oil among Chinese government members, industrial officials, and scholars as reported in various aspects of the media, official publications, and academic papers. Additionally, here we analyse what we see as the facts about China's peak oil, and we show that China is already facing its peak oil problem. Several unfortunate situations caused by the public denial of peak oil are discussed and three potential reasons of the public denial and lack of knowledge are analysed. Lastly, we discuss some actions China should take to deal with its peak oil issue.

1. Introduction

Peak oil refers to a point in time at which oil production ceases to grow. Typically the period around the oil peak is characterized by an undulating plateau punctuated by short periods of increased production followed by periods of decline. This phenomenon may occur at the regional, national, or global level. Hubbert's prediction [1] of a 'peak' in US oil production has spurred a long-lasting and divisive debate on the exhaustion of petroleum resources. In 2003, the Executive editor of the established US-based trade magazine *The Oil & Gas Journal,* noted this debate, and commented that this global issue had become increasingly "polarized and more rancorous – and, especially noteworthy, more politicized" (referenced in [2]).

Though nowadays the emerging US shale industry and low oil price are leading to more scepticism and less interest in peak oil, Chapman argues that the topic of peak oil is still with on-going relevance [3]. In addition, Tverberg has predicted, early in 2012, the fact that oil limits may manifest themselves as low oil prices and a "glut" of oil supply [4].

While this international debate on peak oil is going on in the world, China's academic, government, and industrial media remain largely silent on this issue. On the other hand, since China is the largest oil consumer in the world and its oil consumption is increasing rapidly, while at the same time her domestic production is growing much slower than oil consumption [5], it would seem that peak oil may become an inextricable problem that she has to face.

This paper discusses the status of the debate on peak oil in China, and presents objective analysis of the realities of peak oil in the country. Furthermore, this paper discusses the potential reasons for the public lack of knowledge of peak oil, and suggests some possible actions China should take to deal with its peak oil problem.

2. A Review of Development of the Peak Oil concept in China

China's contributions to the acknowledgment of the issue of peak oil were limited until 1984 when Weng [6] published his "Fundamentals of Forecasting Theory." As a geophysicist and petroleum geologist from the Chinese Academy of Science, Weng designed a model for forecasting long-term oil and gas reserves and production levels. Weng called this model a "Poisson Cycle", because Weng's formula was similar to the probability function of Poisson distribution. This "Poisson Cycle" model was designed to predict the world oil and gas production based on the production levels from the year 1918.

Chen [7], a researcher from the Petro China Exploration & Development Research Institute, expanded this model using trial and error to derive a new non-linear model, entitled the General Weng Model. Until 2005, many Chinese researchers, including Chen and Hu [8], used these models for predicting future world oil and gas production but not specifically referencing it as "peak oil" production and its potential implications.

In 2005 Association for the Study of Peak Oil (ASPO)-China was founded, and this led to the establishment of the Group for the Global Energy System-China, which introduced the concept of "Peak Oil" to Chinese society. Later that year the first paper on peak oil by Zhao et al. [9] was published marking the inception of Peak Oil dialogue within Chinese academia.

Qian [10] published a series of papers to refine the theory and discourse of peak oil in China. His papers, "China will Face Peak Oil in 2015" [11] and "The Current Situation of Oil and Gas Production Peak in China" [12], are aggregations of existing scientific works focused on oil production. While he has remained neutral with regard to the concepts and findings included in his papers, Qian is perhaps the first Chinese researcher to acknowledge the concept of peak oil.

Later on, the issue of peak oil in China has been further researched by several scholars, most of them are ASPO-China members [13-19].

3. The Current Debate about Peak Oil in China

Participants of the debate over peak oil in China can be divided into those that support the concept, those that do not support the concept, and those that remain neutral.

Questions and discussion surrounding this debate have included the following topics: the amount of remaining and recoverable oil and gas reserves; when and if peak oil has/will occur; the role of technology in current and future oil and gas exploration, production, and recovery; and the ability of non-conventional and renewable energy to substitute or compensate for potential reductions in conventional oil and gas production. This paper will conduct a review of this debate within Chinese literature.

3.1 Arguments of different parties regarding Peak Oil issue in China

Chinese energy theorists who argue against the idea of global peak oil believe that international oil prices will regulate oil production and consumption. Some even suggest that limitations on world oil availability are a result of a monopolistic oil trade. For the purposes of this paper these researchers are referred to as "non-supportive" of the peak oil concept.

Zhou, a former leader of the Energy Bureau of the National Development and Reform Commission of China, espouses the view that we are not facing the 'end of the age of oil' but that we are experiencing high oil prices [20]. Zhou believes that it will take a long time to change the situation of oil and gas production and that oil and gas will continue to meet demand for decades to come. He also infers that the perception of oil scarcity is a result of oligopolistic actions on that part of oil producers and oil producing nations.

Wu [21] of the Ministry of Commerce of the China believes that the demand for oil will peak as a product of peak consumption. He concludes that decreases in the oil price will result from a decline in consumption after peak consumption has been reached, rather than as a result of a peak in production. This scenario, she suggests, will effectively render the theory of peak oil moot.

Zhang [22-24] of the Sinopec Research Institute of Petroleum Exploration and Development strongly opposes the peak oil theory. He suggests that while Hubbert's model forecasting peak oil production within the continental United States is relatively accurate, the latter's predictions for world oil production are flawed. Zhang asserts that peak oil models are suitable for simple, static and closed systems such as countries, rather than complex, dynamic and open systems such as world oil production. He claims that world oil production cannot be predicted based on our understanding of current production trends, and/or life cycle assessments of a single well or a small geographic area.

Hu [25], a leader in research policy for the China National Offshore Oil Corporation (CNOOC), argues that peak oil projections are theoretical in practice, having little or no physical evidence to support peak oil projections. According to Hu, Hubbert's global peak oil predictions and other peak oil studies that followed do not adequately take into consideration the accuracy of oil reserves and production data, nor do these predictions take into account technological developments, the impact of price fluctuations, the influence of investment, changes in demand, and the introduction of substitute energies. Hu indicates that peak oil theory is based on studies that do not employ a rigorous scientific approach when dealing with a highly varied and complex world.

There is also another group of researchers that weigh in on the theory of peak oil. These are those who agree with and advocate peak oil theory and its implications. This group includes researchers who are members of ASPO-China, particularly Feng [26], who has published more than 20 peer-reviewed papers about peak oil issues. In addition, Chen [27, 28], Chen and Guo [29], Chen and Zhao [30] and some other researchers [31, 32] do not directly reference peak oil within their writing, but draw similar conclusions. Chen's research, for example, analysing China's oil reserves, indicates that Chinese oil production has likely peaked. In addition, Li, and also Tao, have published papers expressing their support of peak oil theory. Unfortunately, these researchers have not continued to publish in the field of peak oil. Examples of recent papers about China's peak oil issue are those by Wang et al. [17], Wang et al. [18] and Wang et al. [19].

Besides the two groups above, there is also a group of researchers who keep neutral opinions regarding peak oil. These analysts include Xu [33, 34], Guan [35], and Lin [36], and Lin and Liu [37].

3.2 Summary of the Debate

Even though the forecast of oil production commenced in China as early as 1984, our previous discussion of varying points of view in the debate is confined to research in the field of "peak oil" theory occurring within the past 15 years. While this and similar issues have been debated using different terms we restrict our discussion to research that directly mentions the concept of peak oil and its implications. The following (Table 1) is a summary of the aforementioned researchers' published opinions on peak oil.

Table 1 Published Opinions on Peak Oil from Influential Research and Policy Makers in the People's Republic of China.

Peak Oil Position Researcher	Affiliation	Published Statements [a]	Reference(s)
Non-Supportive			
D.D. Zhou	Energy Bureau of the National Development and Reform Commission	We will not enter a post oil age.	[20]
D.H. Wu, 2010	Ministry of Commerce, the People's Republic of China	Peak oil theory will collapse without evidence to support it.	[21]
K. Zhang, 2008, 2009	Sinopec Research Institute of Petroleum Exploration and Development	Peak oil is like a popular song which is made by the media and has an impact on the public.	[22-24]
S.L. Hu, 2010	China National Offshore Oil Corporation	Peak oil theory is just a scare tactic.	[25]
Neutral			
D.M. Xu, 2009	Energy Bureau of National Development and Reform Commission	Technology will decide our energy future and influence future energy production.	[33,34]
Q.Y. Guan, 2010	The Global Macroeconomic Policy of Change Think-tank	We should focus on peak consumption and peak CO_2 emissions.	[35]
B.Q. Lin, 2007; Lin, et al., 2010	China Energy Economic Research Centre at Xiamen University	Peak oil is the basis of China's national oil security strategy and a motivation for conservation.	[36, 37]

Supportive			
L.Y. Feng et al. 2008	China University of Petroleum (Beijing)	Peak oil will occur; We have entered the post-oil age; China's oil production might peak in 2026, with peak production of 196 million tons/yr.	[16, 26]
Y.Q. Chen, 2003; 2005; Chen, et al. 2008, 2009	Research Institute of Petroleum Exploration &Development, China National Petroleum Corp.	Oil production has likely peaked.	[27-30]
Y Li, 2007	Shanghai Alliance Investment Ltd	China's oil production would peak in 2020-2030, with peak production of 216-219 million tons/yr.	[13]
Z.P. Tao et al. 2007	NorthEastern University, China	China's oil production would peak in 2019 and the peak production would be 199.5 million tons/yr.	[14]
J.L Wang, et al. 2015	China University of Petroleum (Beijing)	China's unconventional oil production will peak in 2068 at 0.35 Gt/yr. in the TRR scenario, whereas the peak production in the PR + CP scenario will appear in 2023 and is 0.05 Gt/yr.	[17]
T.T. Wang, et al. 2015	Southwest Petroleum University, China	China's oil production would peak during 2024-2025, with peak production of 209 million tons/yr.	[18]
K Wang, et al. 2016	China University of Petroleum (Beijing)	China's conventional oil has already peaked in the year 2010 and the peak production was 167.5 million tons/yr.	[19]

[a] Statements included within the "Published statements" column of this table have been translated from Chinese and also in some cases edited slightly for clarity.

As is shown in Table 1, the strongest voices against peak oil in China are typically government officials or leaders within the oil industry. Their opinions opposing peak oil are usually published through informal, non-academic information sources, such as industrial newspapers, media interviews, etc.

Those who clearly support peak oil and advocate public policy changes, guided by an understanding and acknowledgement of peak oil theory, are often academics and researchers with little public influence. Their opinions and arguments are generally published in formal academic journals.

Therefore, objective and calm debate regarding the problem of peak oil in China is unfortunately not enough to achieve widespread agreement on this important but still-contentious issue.

4 The Reality of Peak Oil in China

In this section we look at the facts concerning oil production in China.

4.1 Conventional oil production of China has peaked

As shown in Figure 1, Wang et al. indicate that China's *conventional* oil production had already peaked in 2010, with the peak production being 167.5million tons/year; while the continued increase of oil production in China after the year 2010 has been caused by increased production of unconventional oil [19].

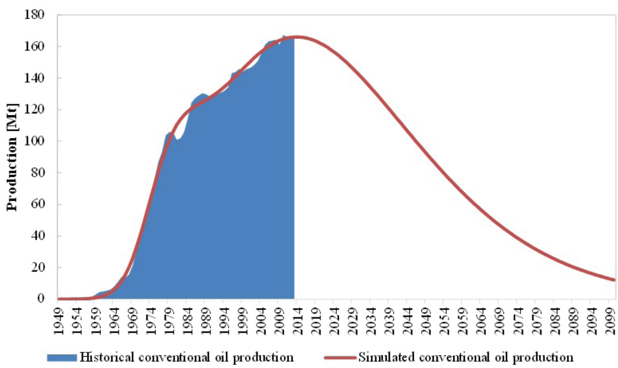

Figure 1. Forecast of China's conventional oil production [19]

Wang et al. (2016) also show that China's unconventional oil can only postpone China's peak year of oil production by about 11 years. Actually, if the likelihood of high development costs, large environmental impacts, and continued low oil prices are considered, the prospect of China's unconventional oil development would probably be even less favourable.

As is illustrated in Figure 2, compared with conventional oil, the equivalent amount of unconventional oil tends to be both more expensive to develop and also tends to produce a larger quantity of greenhouse gases (GHG) in the process of extraction. Thus, there are many uncertainties when considering the substitution of unconventional oil for conventional oil [19]. According to a recent report, in fact China's total oil production (conventional + unconventional) has already peaked in 2015 [38].

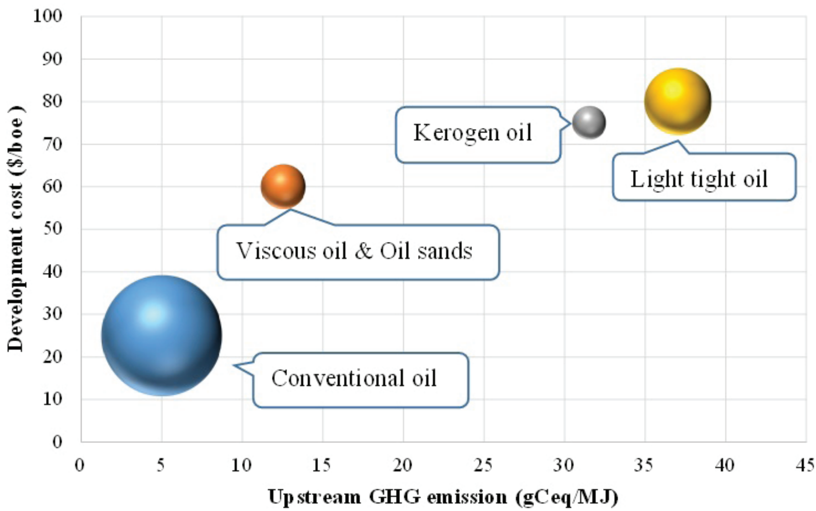

Figure 2. Upstream GHG emission and development cost of different kinds of oil
Note: The size of 'bubbles' in the figure represents URR of certain kinds of oil in China;
Data sources: URR data are from Wang et al. [19]. Development cost data are from IEA [39]; Upstream GHG emission data is from Brandt and Farrell [40].

4.2 Energy Return on Investment (EROI) of China's fossil fuel are declining

Most energy policies calculate energy supply from gross domestic energy production plus energy imports. However, what is important to society is the *net energy* available from these resources [41]. EROI, like net energy, describes numerically how much energy is left to power the modern industrial society after extraction, processing and delivery.

As is mentioned by Hu et al. (2013), the EROI for China's conventional oil and natural gas extraction decreased from a maximum value of 14:1 in 1996 to 10:1 in 2010, with an annual rate of decline of 2.6% , and is estimated to decrease to 9:1 by 2020 [42].

The declining EROI of China's oil and gas extraction indicates that despite the development of technology, the Chinese society is consuming an increasing amount of energy to find and produce its energy due to the declining quality of energy. This, in turn, may be a reflection of the issue of peak oil in China.

4.3 Peak oil may manifest itself in a low oil price

Most people naturally believe that if we encounter oil limits, the impact will be high oil prices and shortage of supply. As is noted by Tverberg (2012), this view may be completely backwards, however, because the world economy is a networked system, and the way feedbacks work is not always obvious. Tverberg has argued that the fact oil limits may manifest themselves as low oil prices and a "glut" of oil supply [4]. Her reasoning concerns the productivity of workers, and for that matter, the productivity of investments in general, when the cost of oil production is rising.

When oil costs are rising, it is taking more workers, and more resources in general, to produce a given amount of oil, say one ton of oil. This is precisely the opposite of a gain in productivity; it is a loss of productivity, because the process is now more complex, and thus more expensive. More workers, more capital goods, and more resources of many kinds are required because deeper or more complex wells are needed, and more advanced technology is required. Therefore, Energy Returned on Energy Investment is falling [43].

Economists often talk about the importance of growing productivity in producing higher wages for workers [44]. Here we are encountering the opposite effect: falling productivity of workers. This type of falling productivity is not generally measured in usual economic analyses, because these typically look at the efficiency of particular step in the process, say, the cost of drilling one foot of oil well. The problem here is that the nature of the process is changing, so that many more feet of oil well are needed to obtain a ton of oil, and many other steps are also needed to be added to the oil extraction process. Viewed in terms of how many tons of oil a typical worker (or a ton of steel) can be expected to produce, productivity falls.

As the cost of producing many types of commodities is rising, due to, in some cases, the diminishing returns (similar to the problem for oil), the world economy is reaching a situation where the cost of producing many commodities is rising, in a way that represents the need for more workers and other resources. This situation might be described as falling productivity of workers and resources. In such an environment, wages are likely to remain stagnant or even decline, even as the cost of many commodities rises. This combination of rising costs and stagnant wages is likely to lead to a slowing economic growth and even recession [4].

One particular problem for workers with wages that are lagging behind is the difficulty of purchasing "big-ticket" items such as new homes, furnishings, or cars. As these items become less affordable for many workers, demand for commodities (such as oil) is reduced for two reasons: (1) Oil is required to make these big-ticket items. (2) These big-ticket items also use oil and other energy products in their operation. It is this lack of demand (really affordability), brought about by falling productivity that can be expected to lead to low commodity prices, such as we are seeing today. These low prices are likely to eventually lead to the end of oil production.

5. Discussion

5.1 Unfortunate situations caused by lack of knowledge (or rejection) of the concept of peak oil in China

As indicated above, it seems very likely that China's production of conventional oil has already peaked. Furthermore, production of its unconventional oil has an uncertain future. However, the mainstream attitude of China's future oil production is almost always quite optimistic.

Looking back over history, several unfortunate situations have been caused by the public denial of peak oil, and over-optimistic estimates of China's future oil production.

The most typical one is was the controversy over the stated 1 billion tons of reserves of the Nanpu Oilfield, which is part of the Jidong Oilfield of CNPC. In May of 2007, Jidong Oilfield published the news through Xinhua News Agency (China's core media) saying that they had found a new oilfield, named "Nanpu", with oil reserves of 1 billion tons, and that the oil production of this Nanpu Oilfield would grow to 10 million tons/yr. by the year 2012 [45]. China's high level media "People's Daily" had also actively reported and advertised the great discovery [46]. According to CNPC, this discovery stemmed from a break-through in petroleum geology theory and in exploration techniques. These advances would greatly improve China's security of oil supply, and became a milestone in the history of China's petroleum industry. Some people even regarded it as the start of another 'golden age' of China's oil discovery. However, in fact, the reserves of the Nanpu Oilfield were seriously overestimated. According to the real data, the oil production of the whole Jidong Oilfield (including Nanpu Oilfield and another affiliated oilfield) in 2013 was just 1.7 million tons/yr., and the recoverable reserves were corrected to 85.7 million tons [47].

Another unfortunate situation was the "Ten Daqing oilfields", which happened in the 1980s. With the discovery of Renqiu Oilfield, China's oil production had finally broken through 100 million tons/yr. level. The government was enthusiastic about China's oil industry, and soon set the target of reaching oil production of 400 million tons/yr. in 2000, and of finding ten Daqing-scale oilfields in 20 years. China's core media all reported this actively, and posts and songs were created in order to broaden this target slogan. However, the reality proved that in the target year 2000, the production of China's conventional oil was only 146 million tons, and the total production of both conventional and unconventional oil was only 163 million tons.

The lesson from these situations is that an attitude of objectivity and calm is important in all oil resource and production forecasts, and that as a nation we should change from over-optimistic attitudes as soon as possible, and instead bravely face reality, and deal intelligently with the approaching problem of peak oil.

5.2 Possible Reasons for the "Invisibility" of Peak Oil in China

It is an interesting question to ask: Why have scientific warnings of peak oil and declining oil availability been generally disregarded by those in power in China? Here we suggest three potential reasons.

The first reason could be the large variations in the estimated/projected ultimate recoverable resource (URR) values for oil resources in China. Several estimates of China's ultimately recoverable oil resources (URR, the total amount of "recoverable oil" that is in the ground prior to extraction) have been generated in the past few decades. The studies involved have produced highly variable URR results, and hence corresponding implications for China's future as a producer of oil. A review of the academic literature during the past 15 years regarding the URR of China's total oil resource (including both conventional and unconventional) shows an average value of 12.2 Gt [19]. At the same time, China's official agency has published quite optimistic URR estimates for China's conventional oil. According to the *New round of oil and gas resources assessment report*, published by China's Ministry of Land and Resources in 2006, China's conventional oil URR is 21.2 Gt [48]; the number was raised to 23.3 Gt in the *Dynamic evaluation of oil and gas resources in China* report published in 2010 [49]; and was again raised to 26.8 Gt in the equivalent report published in 2015 [50]. Because of the optimistic attitude of Chinese official agencies toward oil resources, mainstream opinions tend to ignore the peak oil issue.

The second reason that peak oil has been 'invisible' could be a natural reluctance to acknowledge a theory built on the premise that technological advancement in the field of oil production and efficiency will be insufficient to compensate for diminishing oil availability.

Lambert and Lambert [51] suggest that a society's inability to perceive the danger associated with the depletion of finite resources (with oil being just one example) may be due, in part, to a predisposition to assess future dangers within the construct of the known and familiar. To-date there are few, if any, scenarios in which technological advancements fail to eventually provide society with a satisfactory solution. This suggests that the present-day society may not be able to adequately recognize and define the "danger" associated with peak oil and is, therefore, unable to extrapolate how to act in the presence of this "danger".

Also, Hubbert (1956), when discussing the relation between energy consumption and population growth, stressed that technological advancement could not be looked upon as the ultimate solution. Similarly, Weng's model (1984) limits the discussion of technological advancement and chooses, instead, to focus on resource availability and lifecycle assessments as generally applied to the production of finite resources [6]. Hubbert's and Weng's less-than-optimistic forecasts are difficult to accept in the face of growing production rates and technological advancements that have assisted in this development.

In addition, as mentioned earlier, several studies have been released that call into question Hubbert's ability to accurately predict global peak oil [52; and see 53]. These studies and /or resulting discussions choose to focus on the minutia, limitations, influence of unknown variables, and precision of Hubbert's and Weng's models and findings, rather than on the long-term accuracy of peak oil theory and general consequences associated with diminishing resource availability and uncontrolled population growth. It seems probable that these arguments against models lack sufficient perspective. They, in our opinion, appear encumbered by academic pedantry and, as a result miss the all-encompassing societal issues resulting from oil depletion.

The third potential reason that peak oil has received relatively little attention could be an understandable desire for those in power to minimize the impact that knowledge of this issue might have on China's economic stability and short-term well-being. According to Nevis [54], a crucial cultural concept, central to Chinese management practices is that "being a good member of society and putting group goals before individual needs should govern all practices." This possible collective orientation [55] may reveal a fundamental difference between the Chinese approach to deal with peak oil theory and the more open dialogue more normal in some western nations. If the flexibility and malleability of China's economy has been overestimated, then this could cause Chinese officials to minimize the potential impact of peak oil [56, 57], in an attempt to protect and shield the Chinese people and economy. It is possible that China's government officials are, in fact, aware of the possibility of peak oil, are concerned about imminent economic and societal repercussions, and hence have a desire to minimize public concern while solutions are sought and policy decisions are hammered out.

We posit that each of these possible reasons for the obvious "invisibility" of peak oil in China does not exist within a vacuum. What is much more likely is that there is a synergistic interplay between these psychological, sociological and political influences. We submit that this interactive effect indeed magnifies their influence on current policy decisions and China's economic market.

5.3 What should China do in face of Peak Oil?

There are a number of actions that China can take in the face of peak oil.

Firstly, developing renewable energy is necessary. Since fossil fuels are nonrenewable energy resources, they will all run out some day. Therefore, exploring for more fossil fuel resources cannot entirely solve the energy supply problem, and is thus not a reasonable avenue to take. China has to seek solutions from increasing use of renewable energy. In practice, the renewable energy industry is now being developed quite fast in China. In 2016, China has already become the world's largest producer of photovoltaic power, at 43 GW installed capacity [58]. In addition, China is now leading the world in the production and use of wind power and smart grid technologies [59]. Despite the optimistic development of China's renewable energy industry, energy consumption in China is still dominated by fossil fuels. By the end of 2012 renewable energy only accounted for 9% of China's total energy consumption. In addition, the EROI of the current renewable energy production is still quite low [43]. There will still be a long way for China to go to sufficiently develop its renewable energy industry.

Secondly, improving energy efficiency is another important action China should take to deal with the problem of energy supply. This includes improving efficiency of both energy production and of energy consumption. Since the EROI of the oil and gas extraction industry in China is declining [42], the energy *efficiency* of oil and gas extraction is also declining, due to the depletion of oil and gas resources, and the decrease of oil and gas resource quality. Nevertheless, there are still many things we can do improve the efficiency of energy consumption, e.g. improve fuel consumption efficiency of vehicles through technology innovation, and use energy more efficiently at home. With improved technology, the same amount of energy resources can be used to support the societal development for a longer time.

And last but not the least, China's public have to change their concepts regarding lifestyle. The idea of expanding expenditure and consumption while being richer is not an ideal goal of life. The expectation of more and more fossil energy resource exploration and exploitation, requiring large and ever-increasing investment, is not reasonable, since this cannot solve the problem fundamentally. The public should change their lifestyle to a more environmentally and energetically sustainable way.

6. Conclusions

We suggest that opponents to the concept of peak oil are mostly top-level government officials and leaders within the oil industry. Their opinions of opposing peak oil are nearly always published through informal, non-academic information sources, such as industrial newspapers and media interviews. Those who support peak oil and advocate public policy changes, guided by an understanding and acknowledgement of peak oil theory, are often academicians and researchers but with little public influence. Their opinions and arguments are generally published in formal academic journals. Calm and objective debate in China regarding the question of peak oil is present, but is not yet enough to get opinions to change widely.

Recent analysis indicates that China's *conventional oil* production has already peaked in 2010, and that probably China's total oil production may also have peaked in 2015. In addition, the important EROI of oil and gas extraction in China has been decreasing during the past two decades. The arrival of peak oil seems pretty much certain in China.

Rejections to the concept of peak oil have in the past caused several unfortunate situations, while the mainstream idea in China now is still against peak oil. The potential reasons of the "invisibility" of peak oil in China have been discussed in section 5.2, and include: the large variations in estimated/projected size of the ultimate recoverable resource (URR) of oil resources; a natural reluctance to acknowledge peak oil theory; and perhaps a desire for those in power to minimize the impact that knowledge of peak oil issue might have on China's economic stability and short-term well-being.

In our view, China should change its over-optimistic attitude and objectively recognize the issue of peak oil as soon as possible, bravely face the reality, and deal with the peak oil problem actively. Potential ways to deal with peak oil include: further developing renewable energy, improving energy efficiency, and changing the public's expectations regarding lifestyle.

Acknowledgements

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References

[1] Hubbert, M. K., 1956. *Nuclear energy and the fossil fuels*. The Spring Meeting of the Southern District Division of Production, American Petroleum Institute Spring Meetings. Available online at: http://www.hubbertpeak.com.

[2] Hemmingsen, E., 2010. *At the base of Hubbert's Peak: Grounding the debate on petroleum scarcity*. Geoforum, 41, 531-540.

[3] Chapman, Ian. *The end of Peak Oil? Why this topic is still relevant despite recent denials*. Energy Policy 64 (2014): 93-101.

[4] Tverberg, G. *Oil supply limits and the continuing financial crisis*. Energy 2012; 37(1) 27-34.

[5] BP. BP *Statistical Review of World Energy 2015*. June 2015. http://www.bp.com/statisticalreview.

[6] Weng, W.B., 1984. *Fundamentals of Forecasting Theory*. Petroleum Industry Press, Beijing. (in Chinese)

[7] Chen, Y.Q., 1996. *Derivation and application of Weng's prediction model*. Natural Gas Industry, 16(2), 22-26. (in Chinese)

[8] Chen, Y.Q., Hu J.G., 1996. *Review and Derivation of Weng model*. China Offshore Oil and Gas, 10(5), 317-324. (in Chinese)

[9] Zhao, L., Feng, L.Y., Wang, Z.M., 2005. *Life cycle analysis of oil: comments on Hubbert's peak oil theory*. China Petroleum Enterprise, 3, 50-51. (in Chinese)

[10] Qian, B.Z., 2007. *World oil production will peak: right or wrong?*

China Petrochemical Industry, 3, 52-54. (in Chinese)

[11] Qian, B.Z., 2008. *China will face peak oil in 2015*. Natural Gas and Oil, 26(2), 3. (in Chinese)

[12] Qian, B.Z., 2009. *The current situation of oil and gas production peak in China*. Petroleum Refinery Engineering, 39, 6. (in Chinese)

[13] Li Y, Li DG. *Forecast for China's petroleum production*. China Energy 2007; 29(4):10-12. (in Chinese)

[14] Zaipu Tao, Mingyu Li. *System dynamics model of Hubbert Peak for China's oil*. Energy Policy 2007; 35(4): 2281–2286.

[15] Jing D. *China's oil production might reach its peak in 2020*. The Second China Energy Strategy International Forum. Nov. 2, 2007, Beijing, China.

[16] Feng LY, Li JC, Zhao QF, et al. *Forecast and analysis of China's oil supply and demand based on the peak oil model*. Oil & Gas Journal. January 14th, 2008: 43-47.

[17] Wang J, Feng L, Mohr S, et al. *China's unconventional oil: A review of its resources and outlook for long-term production*. Energy 2015; 82: 31-42.

[18] Wang T, Huang C, Zhang Q, *The peak of China's oil production forecasting and strategies research*. China Mining 2015; 24 (12): 38-44.

[19] Wang K, Xiong Y, Feng L, et al. *The Peak oil production forecast of China: Result after distinguishing conventional and unconventional oil*. 5th IAEE Asian Conference. 2016, Perth, Australia.

[20] Wang, X.Z., 2009. *Is it science or "hoax" of oil price? Discussion on peak oil*. China Economic Weekly, 34, 26-28. (in Chinese)

[21] Wu, D.H., 2010. *Peak oil ideology will be proven inaccurate without need for rebuttal*. China Securities Journal, June 7, page A04. (in Chinese)

[22] Zhang, K., 2008a. *Two prediction of peak oil production using Hubbert's model*. Oil Forum, 6, 22-24. (in Chinese)

[23] Zhang, K., 2008b. *Analysis of oil exhaustion theory from the methodology of oil production peak*. Sino-Global Energy, 13(5), 8-12. (in Chinese)

[24] Zhang, K., 2009. *Discussion on oil peak and oil depletion*. Acta

Petrolei Sinica, 30(1), 154-158. (in Chinese)

[25] Hu, S.L., 2010. *The shadow of peak oil*. China Energy Newspaper, September 27, page 013. (in Chinese)

[26] ASPO-China, 2005. *Introduction to ASPO-China and peak oil research*. Available online at: www.cup.edu.cn/peakoil. (in Chinese)

[27] Chen, Y.Q., 2003. *Prediction of China's oil production and ultimate recoverable reserves*. Oil Forum, 2, 26-31. (in Chinese)

[28] Chen, Y.Q., 2005. *Method for quickly forecasting recoverable reserves and remaining recoverable reserves in oil and gas field*. Xinjiang Petroleum Geology. 26(5), 544-548. (in Chinese)

[29] Chen, Y.Q., Guo, E.P., 2008. *Building and applying a new decline model of oilfield production*. China Offshore Oil and Gas, 20(6), 379-391. (in Chinese)

[30] Chen, Y.Q., Zhao, Q.F., 2009. *Method and application of forecasting remaining recoverable reserves, remaining recoverable degree and remaining reserves-production ratio of oil and gas fields*. Fault-Block Oil & Gas Field, 16(4), 63-67. (in Chinese)

[31] Wan, J.Y. 1994. *Controlled prediction and an evaluation system of oil and gas "resource-reserve-production"*. Acta Petrolei Sinica, 15(3), 51-60. (in Chinese)

[32] Yu Q.T., 2002. *To predict oil production and recoverable reserves of China and USA*. Xinjiang Petroleum Geology, 23(3), 224-227. (in Chinese)

[33] Xu D.M., 2009a. *Technology will decide our energy future*. China Venture Capital, 1, 45-48. (in Chinese)

[34] Xu D.M., 2009b. *Insist on the creation of technology this will expand the market*. China Venture Capital, 4, 6. (in Chinese)

[35] Guan, Q.Y., 2010. *Peak oil will change international politics and the economic domain*. China Securities Journal, June 21, page A04. (in Chinese)

[36] Lin, B.Q., 2007. *Bad and good news of peak oil*. 21 shi ji jing ji bao dao, July 30, page 031. (in Chinese)

[37] Lin, B.Q., Liu, J.H., 2010. *Estimating coal production peak and trends of coal imports in China*. Energy Policy, 38(1), 512-519.

[38] http://thediplomat.com/2015/07/china-peak-oil-2015-is-the-year/

[39] International Energy Agency (IEA). *World Energy Outlook 2010*. 2010. http://www.worldenergyoutlook.org/.

[40] A.R. Brandt, A.E. Farrell. *Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources*. Climatic Change 2007; 84 (2007): 241–263.

[41] Felix E, Tilley DR. *Integrated energy, environmental and financial analysis of ethanol production from cellulosic switchgrass*. Energy 2009;34:410-36.

[42] Hu, Yan, et al. *Energy Return on Investment (EROI) of China's conventional fossil fuels: Historical and future trends*. Energy 54 (2013): 352-364.

[43] Hall, Charles AS, Jessica G. Lambert, and Stephen B. Balogh. *EROI of different fuels and the implications for society*. Energy Policy 64 (2014): 141-152.

[44] Wallis, WA. *Wages, Productivity, and Prices. Foundation for Economic Education*. March 1, 1960. http://fee.org/freeman/wages-productivity-and-prices/

[45] China Daily. *Nanpu output to hit 2.2m tons*. May 9, 2007. http://www.chinadaily.com.cn/bizchina/2007-05/09/content_868517.htm)

[46] People's Daily. *China find billion-ton huge oilfield*. May 4, 2007. http://paper.people.com.cn/rmrb/html/2007-05/04/content_12853126.htm

[47] China's Ministry of Land and Resources. *Table of proved reserves for China's oil and gas resources in each oilfield and gas field 2013*. 2013. (in Chinese)

[48] China's Ministry of Land and Resources: Research Centre for Oil and Gas Resources Strategy. New Round Evaluation of Domestic Oil and Gas Resources. Beijing: China Earth Press; 2005.

[49] China's Ministry of Land and Resources: Research Centre for Oil and Gas Resources Strategy. National Petroleum Resource Assessment 2010. Beijing: China Earth Press; 2010.

[50] China's Ministry of Land and Resources: Research Centre for Oil

and Gas Resources Strategy. National Petroleum Resource Assessment 2013. Beijing: China Earth Press; 2015.

[51] Lambert, J.G., Lambert, G.P., 2011. *Predicting the psychological response of the American people to oil depletion and declining energy return on investment (EROI).* Sustainability, 3, 2129-2156.

[52] Cavallo, A., 2004. *Hubbert's petroleum production model: an evaluation and implications for world oil production forecasts*. Natural Resource Research, 13(4), 211-221.

[53] Lambert, Jessica, and Gail Lambert. *Life, Liberty, and the Pursuit of Energy: Understanding the Psychology of Depleting Oil Resources*. (2013).

[54] Nevis, E., 1983. *Using an American perspective in understanding another culture: Toward a hierarchy of needs for the People's Republic of China*. Journal of Applied Behavioral Science, 19(3), 249-264.

[55] Ock Yum, J., 1988. *The impact of Confucianism on interpersonal relationships and communication patterns in East Asia.* Communication Monographs, 55(4), 374-388.

[56] Rubin, J. 2009. *Why Your World is about to Get a Whole Lot Smaller: Oil and the End of Globalization*. Random House, New York.

[57] Leggett, J. 2005. *The Empty Tank: Oil, Gas, Hot Air, and the Coming Global Financial Catastrophe*. Random House, New York.

[58] http://www.reuters.com/article/china-solar-idUSL3N15533U

[59] https://en.wikipedia.org/wiki/Renewable_energy_in_China

Oil Forecasting: Data Sources and Data Problems – Part 1

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Part-1: Table of Contents

Part-2: Table of Contents

(Part-2 will be published in the next issue of this journal.)

Abstract

Understanding future oil production has often been bedevilled by lack of access to adequate data. To help clarify the situation, this two-part paper examines the availability and quality of the data required for oil forecasting. The paper is intended primarily for those that forecast oil production, but will be of interest also to those who use such forecasts, to judge the quality of the data employed and hence this aspect of a forecast's reliability.

The paper discusses the data by type and by data source, and points out areas where data are unreliable, or where especial care must be taken with their use. In general, *proved* ('1P') oil reserves data should not be used for forecasting, and instead, the oil industry backdated *proved-plus-probable* ('2P') reserves data must be used. In addition, apparent changes in proved reserves data are particularly misleading.

Other areas where considerable caution is needed are in certain production data; in the use of the industry 2P reserves data for specific

countries; in the likely future availability of oil from currently fallow fields; and in use of ultimately recoverable resource ('URR') estimates of conventional oil if these are significantly out of line with the discovery trend.

1. Introduction

This is the first part of a two-part paper that looks at the sources of data needed to make forecasts of oil production, and highlights some significant problems with these data. The paper is not intended to be comprehensive, and reflects simply the knowledge accumulated by the authors over a number of years.

This first part of the paper discusses primarily data by *type* (production, consumption, discovery etc.), while the second part, which will be presented in the next issue of this journal, will focus on data from individual *data sources*, such as the international organisations, governments, general publications and commercial data companies.

Most of the sources discussed give data for both oil and gas, but here we concentrate on the data for oil. These data relate variously to specific wells, reservoirs, oil fields, oil projects (for non-conventional oil), basins and geographical regions - including countries, and also globally. Not covered in this paper are associated data such as oil field geology, location and quantities of seismic shot, pipeline or refinery data, or oil production costs.

2. Data Sources

The oil data discussed here come from four rather different generic types of source:

(i). Data from oil company or government announcements on *individual* wells, fields, and project developments (the latter apply to non-conventional oil). In most cases such data are fairly reliable, though with a caveat on announced reserves in new fields and projects. But considerable effort is needed if a comprehensive set of such data is to be accumulated, sufficient to forecast a country's total oil production, or indeed world production.

(ii). Data from governments on *all individual fields and projects* within their territory. Such datasets are surprisingly scarce, and sometimes incomplete. The only comprehensive generally reliable such datasets known to us are for Norway (from the NPD), UK (BEIS, formerly DECC), France (BEPH), Denmark, US offshore (originally from MMS, now from BOEM & BSEE), and some US states, such as California. (For definitions of these acronyms please see Annex 1.) But even with such generally reliable government data sources, considerable caution is needed with some classes of their data; for example early Norwegian reserves data, and some past and current UK reserves data.

(iii). Comprehensive *public-domain* data sources covering *field, regional or country totals* for a number of countries, *and often also global* data. These data are typically provided by:

- International sources (such as the IEA, OPEC or Jodi).

- National entities that provide international data (e.g., the US EIA, USGS, Germany's BGR, or France's IFP).

- Widely-used publications. These include the BP *Statistical Review of World Energy*, the *Oil & Gas Journal*, and *World Oil*; and more specific publications such as *Campbell's Atlas of Oil and Gas Depletion* (Campbell, 2013). The data here are often fairly reliable, provided care is taken about the classes of oil included. As indicated above, a crucial exception are the data from these sources on *reserves*, where often only the very unreliable *proved* ('1P') reserves data are given, and where these data cannot be used for oil forecasting without combining with extra information.

(iv). Data from *commercial* data providers. The latter companies include IHS Energy, Wood Mackenzie, Rystad Energy, Nehring Associates and Globalshift Ltd., among others. The data from these companies may cover variously wells, assets, fields or projects, and the full datasets tend to be expensive (often very expensive), though some subsets of these data are free. Data from data companies are on the whole reliable, although there are some important exceptions as highlighted below.

3. Categories of Oil

A problem encountered with almost any oil data lies in ascertaining which categories of oil are included. These categories are not rigorously defined in this paper, but general definitions are given in Annex 2. (For more rigorous definitions, see for example the UKERC *Global Oil Depletion* Technical Report 1, Sorrell and Speirs 2009; or the definitions given by Jean Laherrère on the ASPO France website: http://aspofrance.viabloga.com.)

In practice it can be quite difficult to identify which categories of oil are included in any given dataset, and analysts need also to be aware that the definition for any given category (e.g., 'conventional oil') can vary widely. Moreover, a particular problem lies with condensate data, as discussed in Annex 3.

The various categories of oil lead, in turn, to various oil aggregate groupings that relate to production data (and hence also production forecasts). The main groupings are:

- Conventional oil (ex-NGLs): Here this is taken to be largely mobile oil that can be produced by primary, secondary or tertiary recovery methods, and where neither the oil itself needs to be changed (for example, by heating or dissolving in a solvent), nor its surrounding material (for example, by digging up tar sand, or hydraulic fracturing of the low-porosity rock in which the oil resides).
- All-oil: This grouping includes conventional oil as defined above, plus the very heavy oils (including tars sands and Orinoco oil), plus light-tight ('shale') oil produced by 'fracking', plus oil retorted from kerogen; plus NGLs.
- All-liquids: All-oil plus oil from GTLs, CTLs, other 'XTLs' (i.e., oil produced from various 'non-oil' hydrogen and carbon sources, other than gas or coal), plus refinery gain and biofuels.

It is accepted that even within such aggregate groupings there are problems of definition, and these are set out more fully in Annex 2.

Now we turn to the main purpose of this paper, that of examining the available oil data. We start by looking at data on oil production.

4. Data on Oil Production

4.1. Oil production from individual wells, fields and projects

Data on production from *individual wells* are generally only available from individual operators, or from the commercial databases. The exception is the US, where a reviewer of this paper commented: "*US states generally report individual well production for all wells, and in* *a relatively timely manner. The exceptions are Texas, which is slow to report data, taking two years or more to report all results for a given month, and which combines production data from individual wells on a particular lease; and Oklahoma, which is even slower than Texas in reporting data. Many other states - such as North Dakota - quickly report production data that is comprehensive*."

Data on production from *individual fields*, or from *individual projects* in the case of non-conventional oil, are sometimes available from the field or project operators, from government datasets (see the list under Section 2 (ii) above), and from commercial datasets, including that published annually by the *Oil & Gas Journal* (*O&GJ*). In some of these cases data for particular fields or projects are fully absent, or sometimes are missing for extensive periods. The O&GJ data in particular seem to have become more consolidated over the years in various ways, notably by operating company.

Russia in general is not very open about its oil operations, but an exception in terms of data is Lukoil, which publishes detailed information about its own fields (e.g. in http://www.lukoil.com/materials/doc/FactBook/2014/FB_Book_eng.pdf); while Bashneft, Tatneft, Rosneft and others may also release data (see, e.g.:

- www.bashneft.com/files/iblock/c6f/BN_BOOK_eng_WEB.pdf;
- www.tatneft.ru/production-activity/exploration-and-production/oil-fields-development-oil-and-gas-production/?lang=en; http://eng.russneft.ru/structure/info_7299.stm;
- http://www.rosneft.com/attach/0/58/80/a_report_2013_eng.pdf).

In addition, Gazprom reports detailed audited reserves under ABC1 and SPE rules.

For the main Middle East OPEC countries reliable production data by field are not generally available in the public domain.

For China, detailed data for annual production, discovery, and remaining recoverable resources of individual fields are available from internal annual statistics handbooks of the national petroleum companies; while public-domain data on oil and gas field production are available in the oil companies' magazine *International Petroleum Economics*.

Note that even the oil production data by field in the commercial databases are far from perfect; comparison, for example, of IHS and Rystad field production data shows many discrepancies.

4.2 Data on total oil production from regions, countries and globally

Now we turn from field and project production data to data on the total oil production of *regions*, *countries* and also *globally*.

Here the data are generally fairly consistent among the different sources, at least in terms of global totals, provided one is clear about the categories of oil each includes. This is illustrated in Figure 1, which shows global oil production since 1985 as reported by the EIA, IEA, OPEC and the BP *Statistical Review of World Energy*.

Figure 2 shows the data of Figure 1 more explicitly, by plotting the differences between data sources.

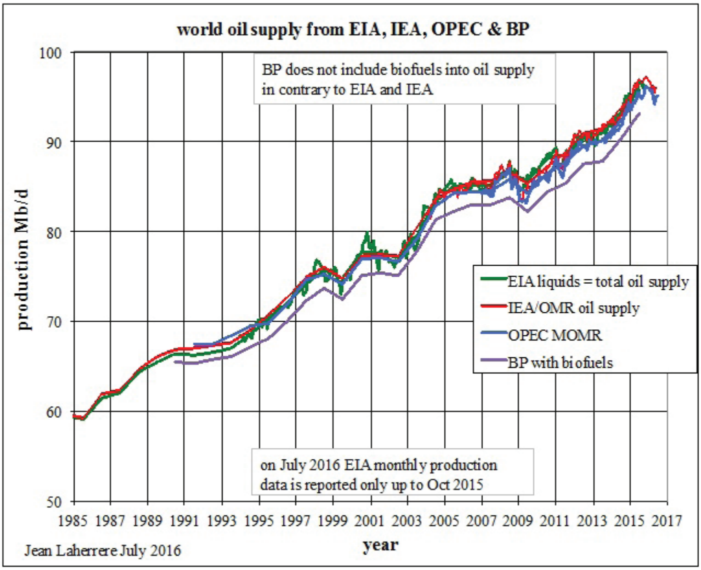

Figure 1. Global Aggregate Liquid Fuels Production data, since 1985.
Notes: - Except for the BP Stats. Rev. data, these data generally relate to 'all-liquids' production, and include the production of crude oil plus condensate, plus NGLs, GTLs & CTLs, and biofuels.
- Data are from current reports. (Data in earlier reports generally differ somewhat for any given year.)
- BP Stats. Review oil production data include "crude oil, shale oil, oil sands and NGLs", but exclude the 'other liquids' of GTLs, CTLs, liquids from biomass, and also refinery gain. (In this chart biofuels production has been added to the BP Stats. production data using information provided elsewhere in their reports.)
Chart: J. Laherrère. Data from the sources quoted.

In looking at Figure 2, in addition to the difference due to the categories of oil included in the BP *Stats*. production data as noted

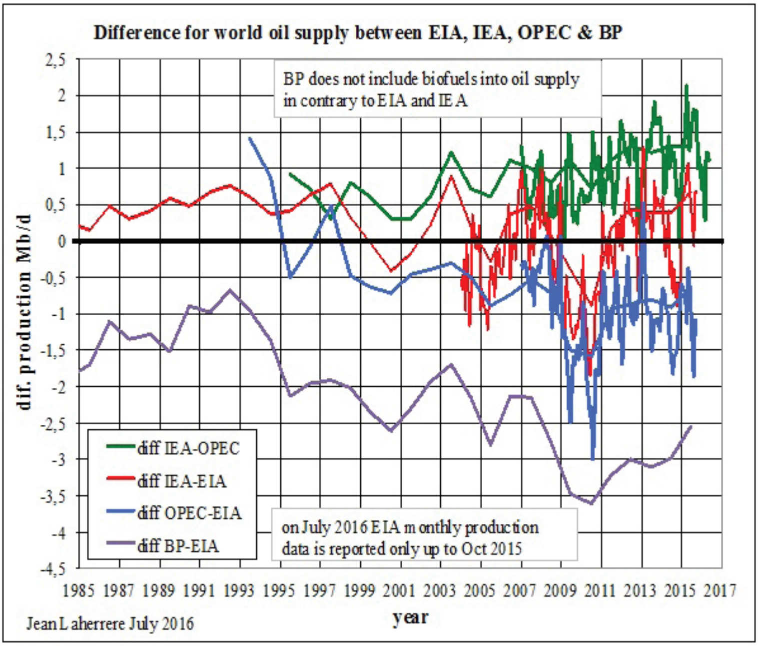

Figure 2. Differences in Global Liquid Fuels Production data, since 1985.
- See note in Figure 1 on the categories of oil included in BP Stats data; and where again biofuel production has been added in this Figure to these data.
Chart: J. Laherrère; data plotted from the sources listed.

in Figure 1, the IEA production data for condensate is sometimes included in crude oil and sometimes in NGLs. As a result only IEA category 'crude+NGL' should be directly compared with EIA category 'crude+NGPL'. If comparison is made between these data sources for the production of crude oil only, this can give rise to discrepancies of up to ~2 Mb/d.

Note that nearly all datasets on oil production have problems, particularly if looking at data for a specific region or country. For example, the BP *Stats*. data in the past have shown odd production totals for Russia in particular; while more recently since 2013 some of these data for specific countries may have double-counted NGL volumes. Similar problems exist for almost all data providers, see

Annex 6 under the individual sources.

4.3 Production by specific categories of oil

When forecasting total oil production it is usually more accurate to forecast the various categories of oil separately, as each has generally different production profiles, production costs and resource limits. For such modelling, it is necessary therefore to know the production data by category of oil. This information is available as follows:

4.3.1 NGPLs, and all-NGLs

Data for production of natural gas plant liquids (NGPLs) and of 'other liquids' can be obtained from a number of sources, including the EIA. Figure 3 shows the latter's data for NGPLs split by country since 1980.

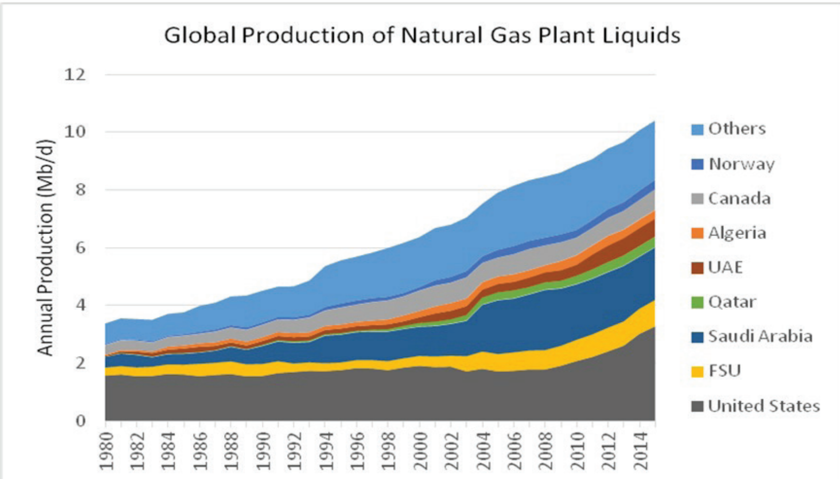

Figure 3. Global Production of Natural Gas Plant Liquids (NGPLs) by Country, 1980 – 2015.
Note: 'Others' include countries where 2015 production of NGPLs was <300kb/d.
Source. J. Wang / R. Bentley; data from the EIA.

As Figure 3 shows, the global production of NGPLs has grown steadily, both with the increased production of gas (including shale gas in the US), and with the installation of plant to extract liquids from gas streams.

4.3.2 Canadian oil sands

Canadian synthetic crude ('syncrude') production is reported by Statistics Canada; and see also data from Natural Resources Canada, and the Canadian Association of Petroleum Producers (CAPP). The latter in its handbook gives the most complete data on oil & gas in Canada. Figure 4 compares a CAPP forecast made in 2011 for Canadian oil sands production with that from 2015.

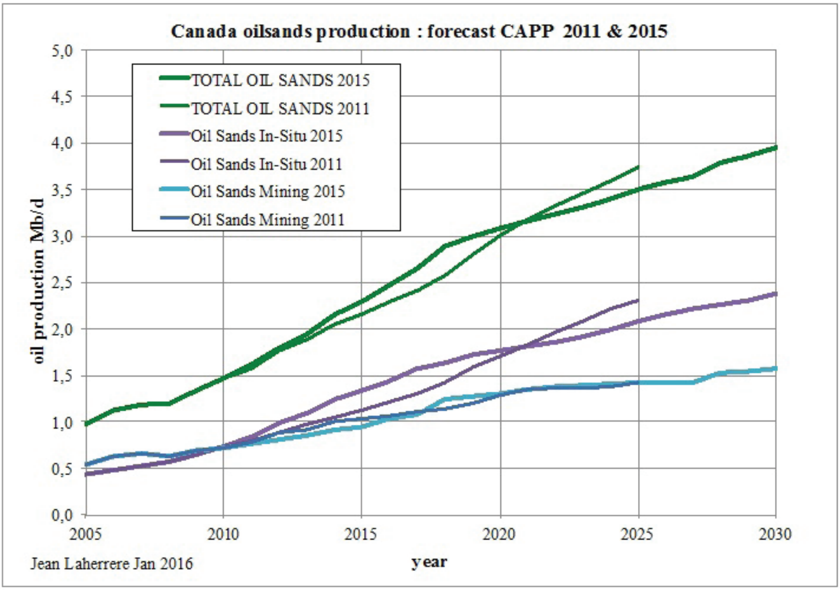

Figure 4. CAPP oil sands forecasts as of the 2011 & 2015 editions of their Handbook.
As can be seen, CAPP have somewhat lowered the trajectory of their forecasts, and now expects total oil sands production to reach about 4 Mb/d by 2030.
Source. Jean Laherrère, 2016.

Some care is needed with oil-sand production data in that the user needs to be clear whether the data report extracted bitumen, or the volume of syncrude produced. In addition, note that the Alberta Oil Sands Industry Update (or Quarterly Update – see e.g. http://albertacanada.com/files/albertacanada/AOSID_QuarterlyUpdate_Winter2015.pdf) gives a government review of oil-sand projects in terms of operating capacity and expected development, although actual production data are not given.

4.3.3 Orinoco oil (Extra-heavy oil from Venezuela's Orinoco basin).

Orinoco oil is also extra-heavy oil, as is the Canadian oil sands, but in the reservoir at perhaps 55°C, against 5°C or so for oil sands. The latter's viscosity is such that oil is classed as bitumen (>10 000 cP), and hence needs heating, usually by steam, to flow. Orinoco oil by contrast can be produced directly without heating by a progressive-cavity pump. But in this case flow rates are typically moderate, of the order of only 1000 b/d, and the recovery factor is low, at around 8%. If steam-heating is applied to Orinoco oil, the recovery factor can be increased to over 25%. The problem with Orinoco oil is that the government nationalised the foreign producers, and in recent times many judge that PDVSA has not been well managed. Production of this oil can undoubtedly increase significantly, but this will need investment and good management.

In terms of data on Orinoco extra-heavy oil production, these are unreliable because PDVSA in their annual report mix data on heavy and extra-heavy production, and where the production of Faja Petrolifera del Orinoco (FPO) is partly extra-heavy. It is almost impossible to get reliable Orinoco extra-heavy production in 2015. This is borne out by Figure 5, which shows Venezuelan extra-heavy production, together with FPO data and 2011 forecasts of production of this oil from the IEA's *WEO* and the EIA's *IEO*.

Other such production data can be mined from company and news reports on the internet, although these are always difficult to reconcile with national total production; and because such reports are usually forward-looking tend to be optimistic.

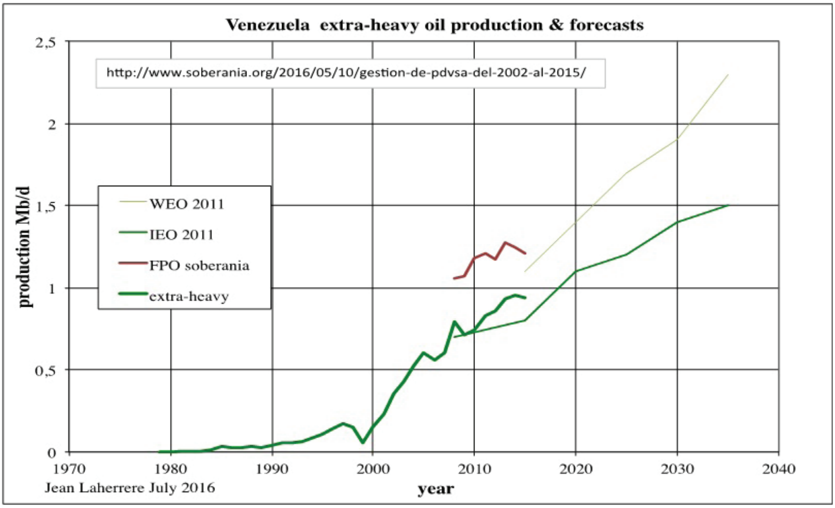

Figure 5. Venezuelan Extra-heavy oil production, and Forecasts
Legend:
- WEO 2011: Forecast of Venezuelan extra-heavy oil production from the IEA's 2011 World Energy Outlook.
- IEO 2011: Forecast of Venezuelan extra-heavy oil production from the EIA's 2011 International Energy Outlook.
- FPO: Production data from the company Faja Petrolifera del Orinoco, but where this includes lighter oil as well as extra-heavy.
- extra-heavy: Laherrère's calculation of Venezuelan extra-heavy production.

Source: J. Laherrère.

4.3.4 Light-tight oil ('LTO')

Also called 'shale oil' (but see 'kerogen', below), this is oil from low-permeability reservoirs in or close to source rocks, produced by use of high-pressure hydraulic fracturing ('fracking') of the rock, and by keeping these fractures open by use of proppants. Currently virtually all production is from the US, though this will probably change.

US LTO data:

US light-tight oil data are now generally available, but not always comparable. The EIA now publishes tight oil production figures by play for the whole US:

http://www.eia.gov/energy_in_brief/article/shale_in_the_united_states.cfm and pretty comprehensive LTO data output for Bakken, Eagle Ford, Haynesville, Marcellus, Niobrara, Permian and Utica plays are at:

http://www.eia.gov/petroleum/drilling/#tabs-summary-2.

But given the problems of data collection, it is perhaps not surprising that EIA LTO production data from different sources (such EIA data on US oil reserves, or from their *AEO* and *DPR* reports) give somewhat different values.

US LTO production data are also available from individual states. For example, Utica data are available from the Ohio Department of Natural Resources; Bakken data are published by the North Dakota Department of Natural Resources in their *Drilling and Production Statistics*; and see also Montana data; while Eagle Ford data are published by the Texas Railroad Commission.

Other sources are given in a list that Mason Inman has put together on oil and gas data sources generally: https://web.archive.org/web/20150219084050/http://www.beaconreader

.com/mason-inman/my-data-sources-a-living-compendium

Production data for US light-tight oil by selected plays is given in Figure 6.

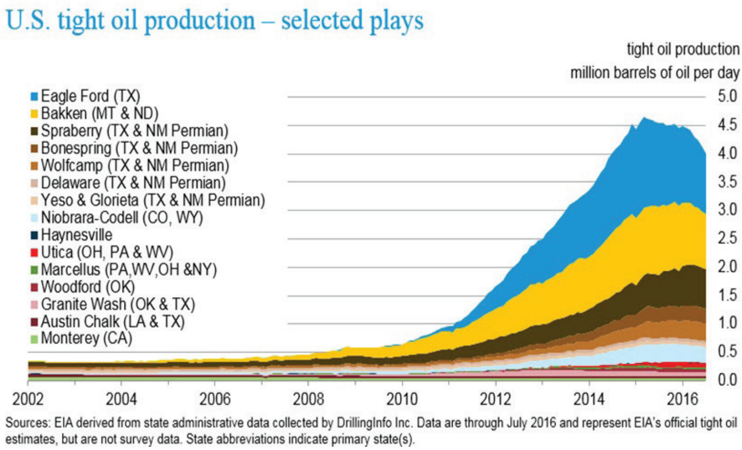

Figure 6. US Light-tight (LTO) Oil Production from Selected Plays, 2002 – July 2016.

Source: www.eia.gov/energy_in_brief/article/shale_in_the_united_states.cfm#tightoil

and see 'Sources' as listed on the chart.

As the Figure 6 shows, US LTO production from these plays reached a maximum in early 2015, and fell significantly from early-2016 as the effect of the fall-off in drilling rigs in use became apparent.

Somewhat different data are given in Figure 7, which shows LTO production from all US plays as reaching a maximum of 5.5 Mb/d in 2015, vs the 'selected plays' maximum of ~4.6 Mb/d in Figure 6.

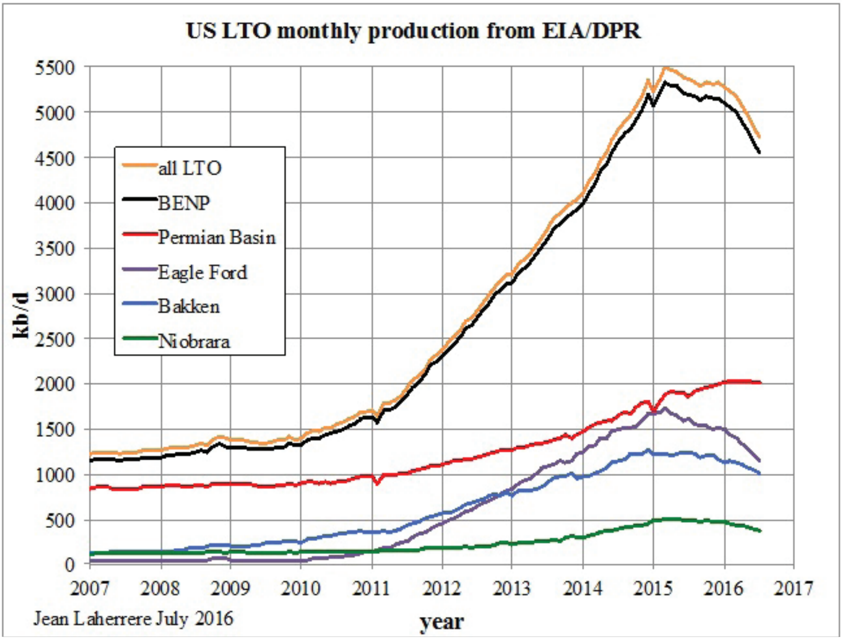

Figure 7. Total US Light-tight (LTO) Oil Production, and from some Basins, 2007 – June 2016.

Note: EIA DPR reports all LTO, but where only four basins ('BENP' = Bakken, Eagle Ford, Niobrara and the Permian Basin) represent the majority of the total. Source: J. Laherrère.

Note that some EIA LTO Permian Basin data mix LTO with EOR data. This is indicated by Figure 8, which shows data on US LTO production by basin from Rystad Energy, where here production of Permian Basin tight oil starts in about 2009, whereas the EIA data (Figure 7) shows this as already at 0.9 Mb/d by this date.

A reviewer of this paper writes: *"The DPR numbers are for all oil and gas produced in the 'region' of a tight oil or shale gas play. The DPR documentation (http://www.eia.gov/*

> *petroleum/drilling/pdf/dpr_methodology.pdf) says:* "Each DPR Region encompasses a specific set of counties, and is not limited to the formation name used for the region." *The numbers reported in the AEO, and on the new webpage for reporting production of individual shale gas and tight oil plays, (http://www.eia.gov/energy_in_brief/article/shale_in_the_united_states.cfm) are only for tight oil and shale gas, so they are lower for each play than that reported in DPR. If Rystad's numbers are compared against the AEO data, or EIA's reporting production individual shale gas and tight oil plays, then the match is very close."* The reviewer goes on to say: *"I generally avoid using DPR for the reasons above, and also because it mixes together historical data and forecasts, without specifying where historical data stops and forecasts begin."*

This example bears out the notion that classification of oil by category in the real world can be difficult, and that analysts should

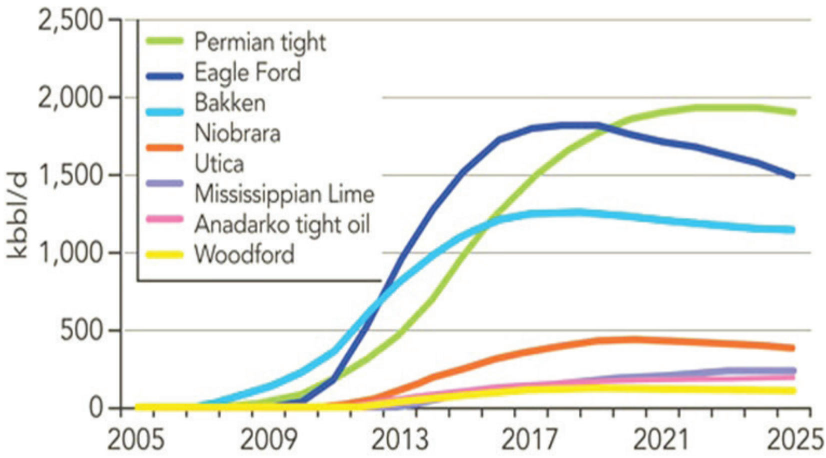

Figure 8. Rystad Energy History and Forecast of Light Oil Production from the Top Producing Plays in the US, 2005 – 2025.

always question the data they use.

Figure 8 in turn helps introduce an important topic: that of what to expect from LTO production going forward, both in the US and in elsewhere in the world?

As readers will know, among oil forecasters there are currently two quite different views on this. For the case of the US, Figure 8 from Rystad Energy takes one view, that of total US production likely in decline from 2025 or so; while Figure 9 gives the opposite view, in this case that of the EIA, of total US LTO production soon picking up again from its post-2015 decline, and increasing steadily (though at a far slower rate than in the past) out to 2040 and beyond. This difference in view on both US and global LTO production going forward is one

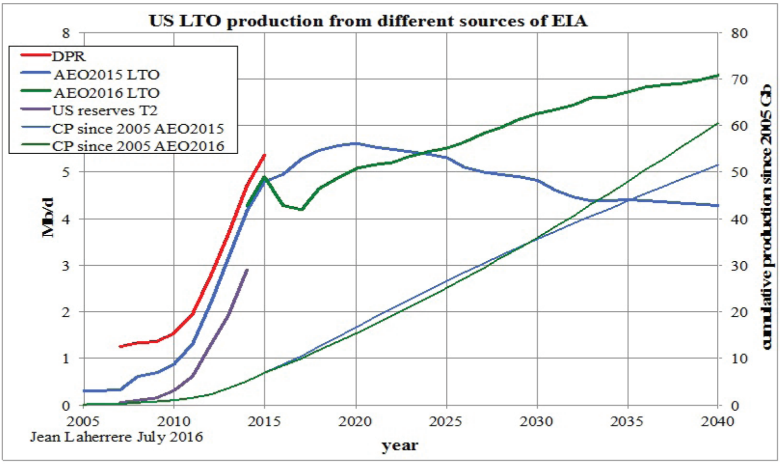

Figure 9. History and Forecasts (out to 2040) of US Light-Tight Oil Production from different EIA sources.
Legend:
Left-hand scale:
- DPR: EIA Drilling Productivity Reports.
- AEO2015 LTO: EIA Annual Energy Outlook, 2015, data for annual US production of flight-tight oil.
- AEO2016 LTO: ditto; data from 2016 Outlook.
- US reserves T2: EIA Form EIA23L – Annual Survey of Domestic Oil and Gas Reserves, 2013 and 2014.

Right-hand scale:
- CP since 2005 AEO2015: Historical (since 2005) and forecast cumulative US production of light-tight oil from EIA Annual Energy Outlook, 2015
- CP since 2005 AEO2016: ditto; data from 2016 Outlook.

Source: J. Laherrère.

of the distinguishing features between current forecasts, and is one which those who use such forecasts should be aware.

As can be seen in Figure 9 and discussed earlier, DPR data for the production of US are somewhat greater than the corresponding *AEO* data. In terms of cumulative production of this oil, this is forecast in the 2016 *AEO* to reach 60 Gb by 2040. This relates to the important question of likely URR values by category of oil, discussed elsewhere in this paper.

Next we examine data on light-tight oil production in Canada.

Canadian LTO data:

Production data of Canadian LTO can be estimated from Natural Resources Canada data, and other sources. Figure 10 gives data to 2011 for Canadian tight oil production by play, while Figure 11 gives more recent data on this split by province. In Canada oil from the Bakken is reported in conventional oil as Western Canadian Sedimentary Basin

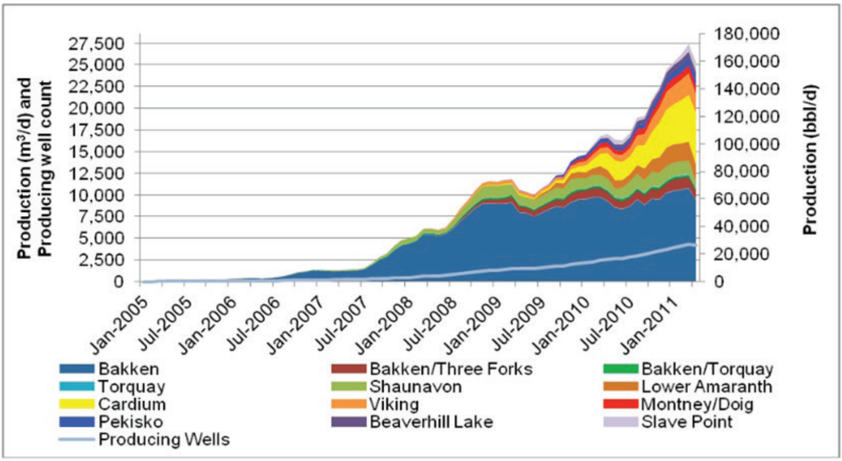

Figure 10. Canadian Tight Oil Production by Play, Jan. 2005 – Jan. 2011. Source: Divestco.

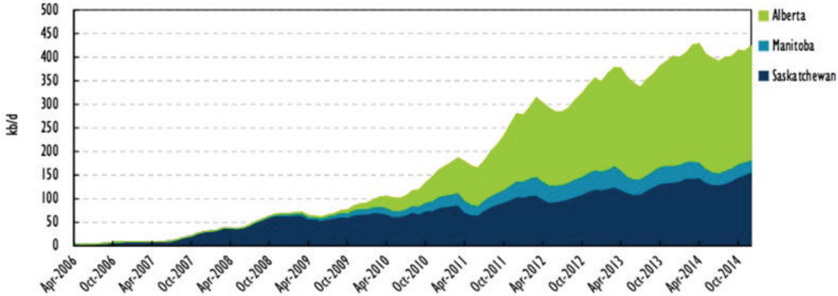

Figure 11. Canadian Tight Oil Production by Province, 2006 – 2014.
Source: Canadian National Energy Board, 2015.

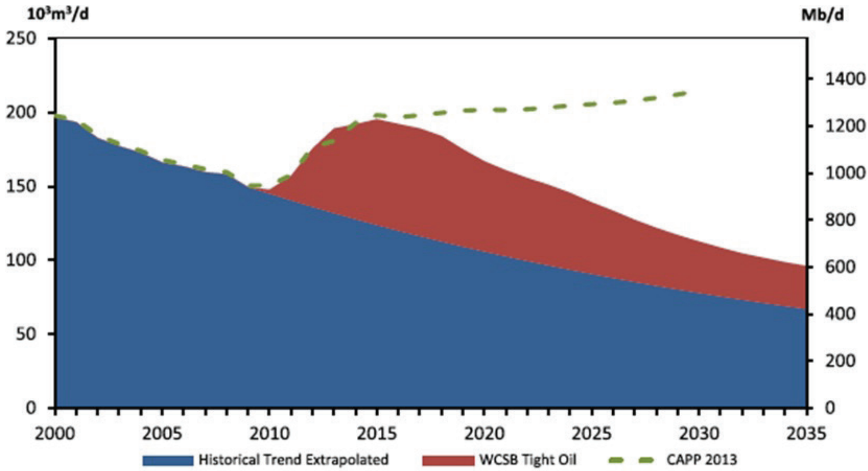

Figure 12. Production of LTO from the Bakken in Canada, shown as 'Western Canadian Sedimentary Basin (WCSB) Tight-Oil'.
Sources: CAPP: Canadian Association of Petroleum Producers; 2013 report.
Canadian National Energy Board 2013: Canada's Energy Future to 2035, page 41; http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2013/nrgftr2013-eng.pdf

(WCSB) tight-oil. In a Canadian National Energy Board report in 2013 production of this oil is shown as peaking in 2015, in contrast to the CAPP view at the same date; see Figure 12.

4.3.5 Kerogen oil

Kerogen oil (or 'source rock oil') is oil produced by heating of the oil pre-cursor, kerogen, found in source rocks that are still immature, i.e., have not received sufficient heating within the earth's crust. This heating (pyrolysis) can be done either *in situ* below ground, by partial burning in an injected source of oxygen, or in a purpose-built plant above ground.

Production of kerogen oil has so far been small: in France from the Autun source from 1830 to 1959 (Figure 13); in Scotland over a similar period, and more recently also from Germany, Estonia, China and Brazil (Figure 14); and with production in Australia from 2000 to 2004.

If not constrained by climate-change considerations, production

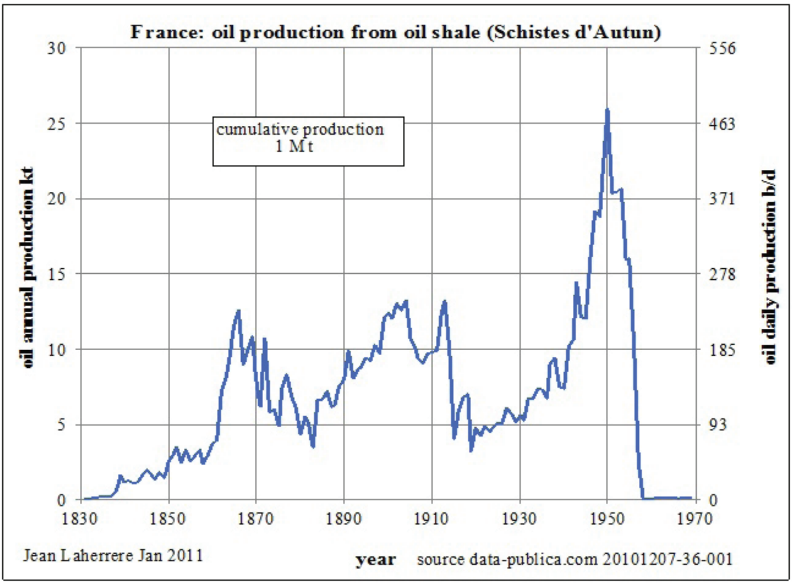

Figure 13. Production of Kerogen Oil in France, from Schistes d'Autun, 1830-1970.

Source: Jean Laherrère, from data-publica.com, see chart.

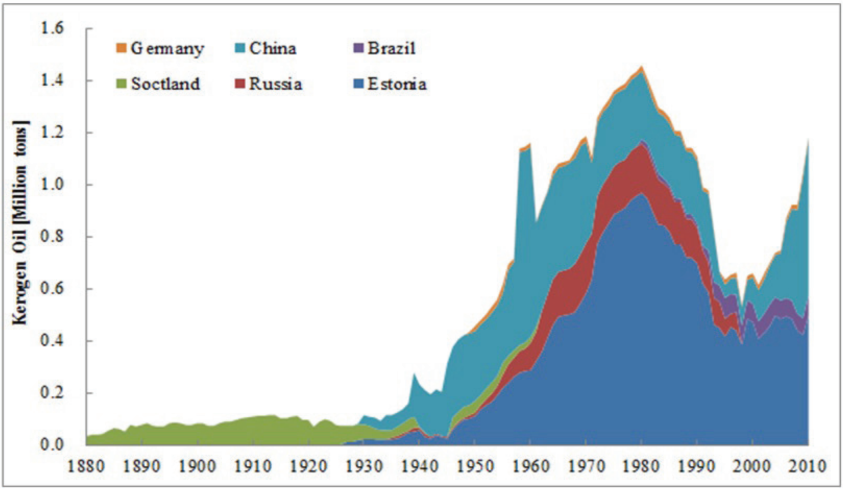

Figure 14. Annual Production of Kerogen Oil in the Countries shown, 1880 - 2010.

Source: Jianliang Wang, see sources listed in the text.

of oil from kerogen can be expected to ramp up significantly in the future, including from new regions such as Jordan, once the global supply of conventional oil becomes severely constrained, and the oil price is high enough.

Data on kerogen oil production generally have to come from various published papers. The data in Figure 14, for example, are from:

- Allix, P. and Burnham, A.K. (2012). Note that this gives production of oil shale rock in tons, and is converted here to kerogen oil production by multiplying by 0.031, the conversion factor set out Qian et al. (2003) where producing 1 metric ton of kerogen oil requires about 33 tons oil shale.

- The more recent data on Chinese production are from: for 1996 - 2010: Zhu, J. et al. (2012) (and where this production is somewhat higher than given in Allix and Burnham); for 2011: Li, S.Y et al. (2012); and for 2012: Li, S.Y et al. (2013).

Other useful data sources quoted by Laherrère include:

- A. Salvador (2005). AAPG *Studies in Geology*, vol. 54.

- A. Burnham (2015). AAPG Explorer, May, p70; and where the latter forecasts significant growth of kerogen oil production in China.

Because of the variety of data sources, and the need to assume sometimes a conversion factor from tons of shale mined to quantity of oil produced, some uncertainty in the results is to be expected.

4.3.6 Gas-to-liquids (GTLs) and Coal-to-liquids (CTLs)

Production of these sources of oil is currently minor, but as with oil from kerogen, would be expected to increase significantly, subject to constraints on CO_2, once the oil price is high enough.

The IEA give some data on production of these oils, but full data on the production of GTLs and CTLs are generally not available from a single source, and must come from a variety of published papers. Much of CTL production to-date has been from South Africa, partly as a result of being under oil embargo, and where the Sasol Company has produced almost 1.5 Gb of synthetic fuel from about 800 million tonnes of coal since the first sample of synthetic oil from coal was produced at its plant in August 1955.

4.3.7 Biofuel

Biofuels are oils produced from biomass, but where this is directly from crops such as oil seeds (by pressing and cleaning), from corn, sugar cane or similar crops by fermentation to produce alcohol, or from other plant material including cellulose following enzyme treatment.

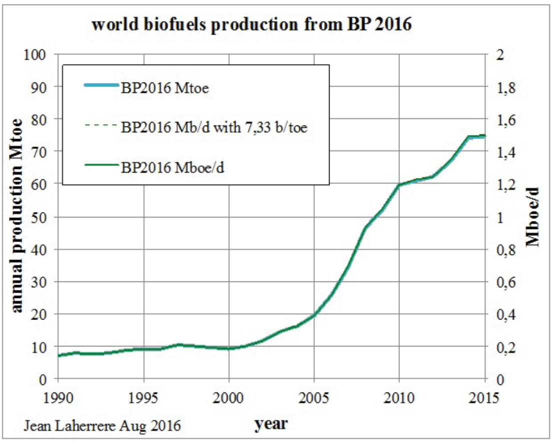

Figure 15. World Biofuels Production, 1990 - 2015.
Note: BP converts biofuels from Mb/d to Mtoe using 7.33 b/toe.
Source: J. Laherrère, from BP Statistical Review, 2016.

The US EIA includes biofuels in its 'other liquids' category, while specific data on biofuel production are in the BP *Stats. Review* supplement on renewable energies, available on the BP *Stats. Review* website; Figure 15.

4.3.8 'Other XTLs' (i.e. excluding oil from kerogen; GTLs and CTLs; and biofuels)

The forecasting methodology of one of us (Laherrère) breaks oil production into a number of categories, one of which is 'XTLs'. This is defined to include oil from kerogen plus GTLs and CTLs, but also synthetic oil produced from other sources such as hydrogen, or from biomass other than as biofuels (for example, via pyrolysis). Production data for kerogen oil, and GTLs and CTLs have been discussed above. Production of the 'other XTLs' is currently very small, and is likely to remain modest for reasons of low EROI ratios and cost.

4.3.9 Refinery gain

Refinery gain is the volume increase that occurs as high-density crude oil is turned into lower-density products such as petrol and diesel fuel

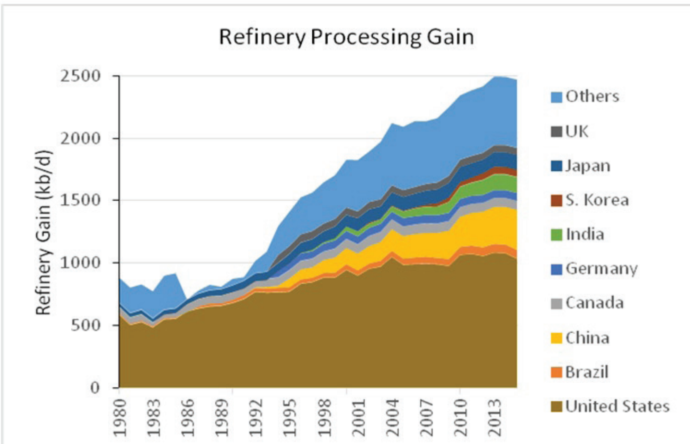

Figure 16. World Refinery Processing Gain by Country, 1980 - 2015.
Notes: - As can be seen, the US is the largest contributor.
- Anomalous data from about 1985 to 1995 for some countries may be due to missing data, or some other cause.
- 'Others' include countries where 2015 refinery gain was <50kb/d.
Source. J. Wang / R. Bentley; data from the EIA.

in a refinery. In volume terms it is an important part of oil supply (as large as extra-heavy production), but does not represent additional energy.

Annual data on refinery gain by country are published by the EIA, see Figure 16; while the IEA World Energy Outlook presents summary data.

4.3.10 Comparison of oil production data

We conclude this section on oil production data by presenting three

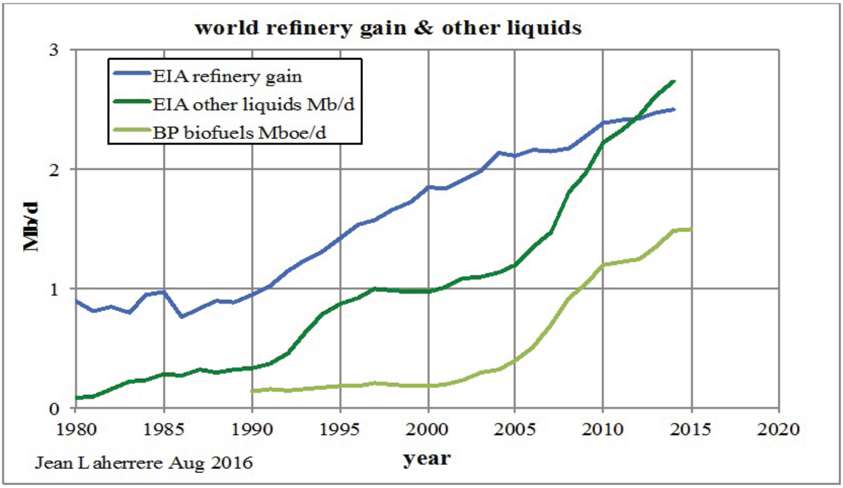

Figure 17. Comparison of World Annual Production of Biofuel, EIA 'Other Liquids' (which includes biofuel), and Refinery Gain.

Note: EIA 'other liquids' includes biodiesel, ethanol, liquids produced from coal, gas, and oil shale, Orimulsion, and other hydrocarbons.

Source: J. Laherrère, from the sources listed (where 'BP' means BP *Stats. Review.*)

charts that compare the data above; and set these data into the context of forecast future production.

Figure 17 compares the annual production of biofuel, of the EIA's 'other liquids' category (which includes biofuel; see the Figure caption),

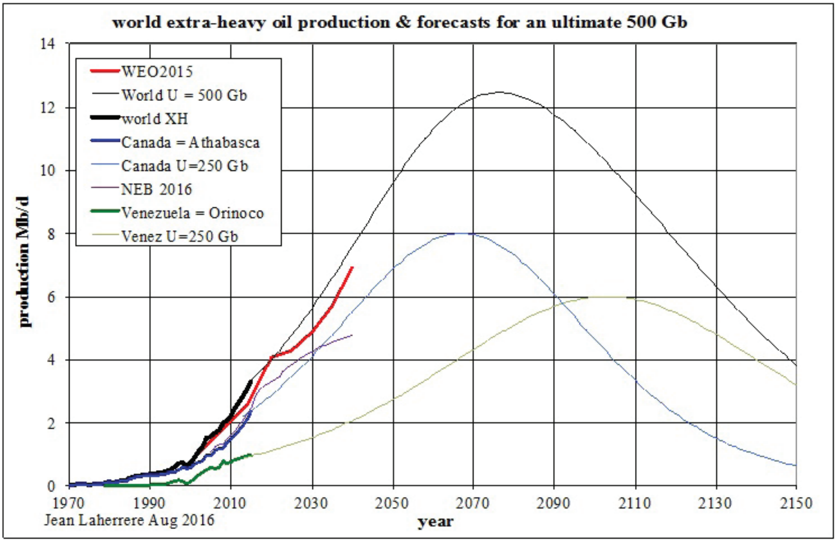

Figure 18. World Annual Extra-heavy Oil Production by Category, and Total; and Forecasts.

Legend:

- WEO 2015: IEA World Energy Outlook 2015 forecast of extra-heavy oil production to 2040.
- World U = 500 Gb: A forecast of world extra-heavy oil production to 2150 based on a 'Hubbert' curve and an assumed URR of 500 Gb. The latter comprises 250 Gb of tar sands oil from Canada and 250 Gb of Orinoco heavy oil.
- world XH: Annual production, 1970 to 2015 of extra-heavy oil.
- Canada = Athabasca: Actual production of Canadian extra-heavy (primarily Athabasca tar sands) oil production, 1970 to ~2015.
- Canada U = 250 Gb: Forecast of Canadian extra-heavy oil production to 2150 based on a 'Hubbert' curve and an assumed URR of 250 Gb.
- NEB 2016: Canadian National Energy Board 2016 forecast of Canadian extra-heavy (primarily Athabasca tar sands) oil production to 2040.
- Venezuela = Orinoco: Annual production of Orinoco oil, 1970 to ~2015 (but see caveat on these data given earlier).
- Venez U=250 Gb: Forecast of Orinoco oil production to 2150 if based on a 'Hubbert' curve and an assumed URR of 250 Gb.

Source: J. Laherrère, from sources listed.

and refinery gain. In total the EIA's 'other liquids' plus refinery gain currently contribute annually some 5 Mb/d of production.

Figure 18 compares data on world production of the 'extra-heavy' oils vs. a number of categories, as well as total extra-heavy oil as defined by Laherrère. The Figure also gives a number of forecasts for these oils.

The main conclusion from Figure 18 is that although production of the extra-heavy oils have been growing rapidly, and continue to grow rapidly in forecasts from the IEA and Canada's NEB, total production of these oils is expected - at least on currently envisaged URR values - to peak at a fairly modest level, of below 15 Mb/d; with individual peaks at ~8 Mb/d and ~6 Mb/d for Canadian tar sand and Orinoco oil,

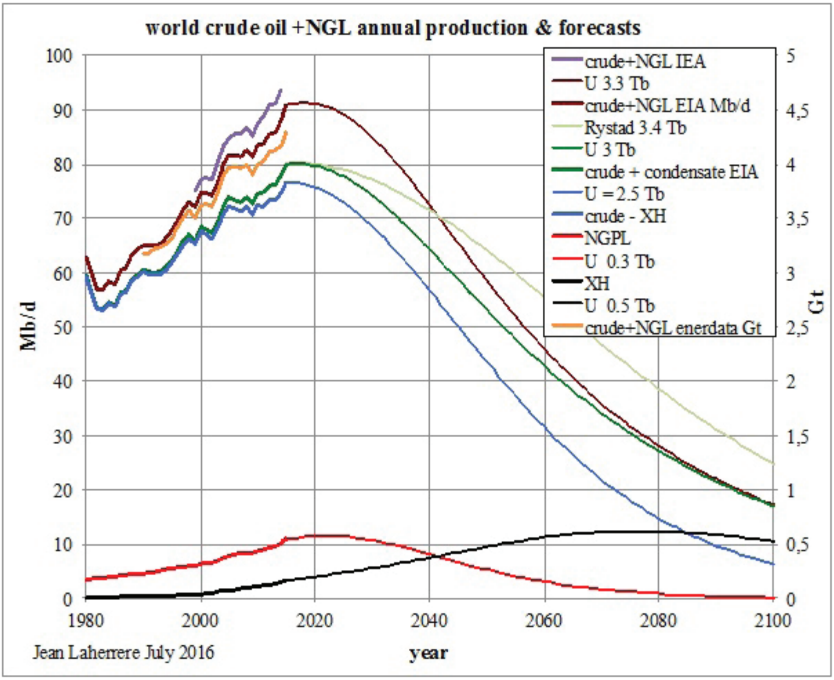

Figure 19. Global Annual Oil Production plus Condensate, or plus NGLs, since 1980.
Also shown are Laherrère's forecasts for future production by category of oil out to 2100.
Legend:
- crude+NGL IEA: IEA data for global annual production of crude oil plus NGLs.

- U 3.3 Tb: Hubbert (logistic) curve based on a URR of 3.3 Tb, fitted to match the data of the ‘crude+NGL EIA Mb/d’ curve. For details of this and the other URR-based production projections shown in this Figure see Laherrère (2015).
- crude+NGL EIA Mb/d: US EIA data for global annual production of crude oil plus NGLs
- Rystad 3.4 Tb: A forecast by Laherrère reflecting Rystad Energy’s URR of 3.4 Tb. As the chart indicates, this is taken as indicating production of crude + condensate (i.e., excluding NGPLs).
- U 3 Tb: Hubbert curve based on a URR of 3 Tb, fitted to match the data of the ‘crude + condensate EIA’ curve.
- crude + condensate EIA: US EIA data for global annual production of crude oil plus condensate.
- U = 2.5 Tb: Hubbert curve based on a URR of 2.5 Tb, fitted to match the data of the ‘crude - XH’ curve.
- crude – XH: Laherrère’s calculation of global annual production of crude oil plus condensate less extra-heavy oils (primarily tar sands and Orinoco oil).
- NGPL: Laherrère’s calculation of global annual production of natural gas plant liquids.
- U 0.3 Tb: Hubbert curve based on a URR of 0.3 Tb, fitted to match the data of the ‘NGPL’ curve.
- XH: Laherrère’s calculation of global annual production of the extra-heavy oils.
- U 0.5 Tb: Hubbert curve based on a URR of 0.5 Tb, fitted to match the data of the ‘XH’ curve.
- crude+NGL enerdata Gt: Enerdata data on global annual production of the crude oil plus NGLs.

Note: This chart may look somewhat complex, but should be read as follows:

- Top three curves: Historical production data from three sources (IEA, EIA and Enerdata), and Laherrère’s projection, of global annual production of crude oil plus NGLs.
- Next curve (green, and light grey): Historical EIA production data, and two projections (Laherrère’s, and Rystad Energy’s) of production of crude oil plus condensate.
- Next curve (blue): Historical data, and Laherrère’s projection, of production of crude oil plus condensate less the extra heavy oils.
- Lower two curves (red and black): Historical data, and Laherrère’s projections, of production of NGPLs, and of the extra heavy oils, respectively.

respectively.

Finally in this section, Figure 19 sets the production data of all oils by category into context. The figure shows annual oil production plus condensate, and plus NGLs, since 1980 from different data sources, and also Laherrère's forecasts for future production by category of oil out to 2100.

The main conclusions from Figure 19 are that on the URRs indicated (see Laherrère, 2015), and if a simple 'peak at approximately mid-point' model is used, then:

- global production of NGPLs peaks at a bit over 10 Mb/d in perhaps 5 years or so, roughly in line with the expected peak of global *conventional* gas supply;

- global production of the extra-heavy oils (mainly Canadian tar sands and Orinoco oil) peaks at a bit under 15 Mb/d by perhaps 2080; as shown in Figure 18;

- global production of all crude-plus-NGLs is likely to be at peak about now.

In the latter case, it is recognised that the global production of a variety of 'other liquids' (including oil from kerogen, CTLs and GTLs, and biofuels; and possibly of fully-synthetic oil produced from ubiquitous feedstocks provided adequate cheap energy is available, such as from grid-surplus renewable energy) can increase in future where not subject to CO_2 constraints. But for a society that still largely functions on widely-available and relatively inexpensive 'all-liquids' production, this aspect of its energy future appears to be in question.

5. Data on Oil Consumption

Now we turn from data on oil production to data on oil consumption. Not surprisingly, such data are never fully comparable with production data for a variety of reasons; partly due to changing volumes in storage, but also due to the different reporting sources that are used, where consumption generally measures end products, while production measures oil extracted from the ground.

Data on oil consumption are available from a number of sources,

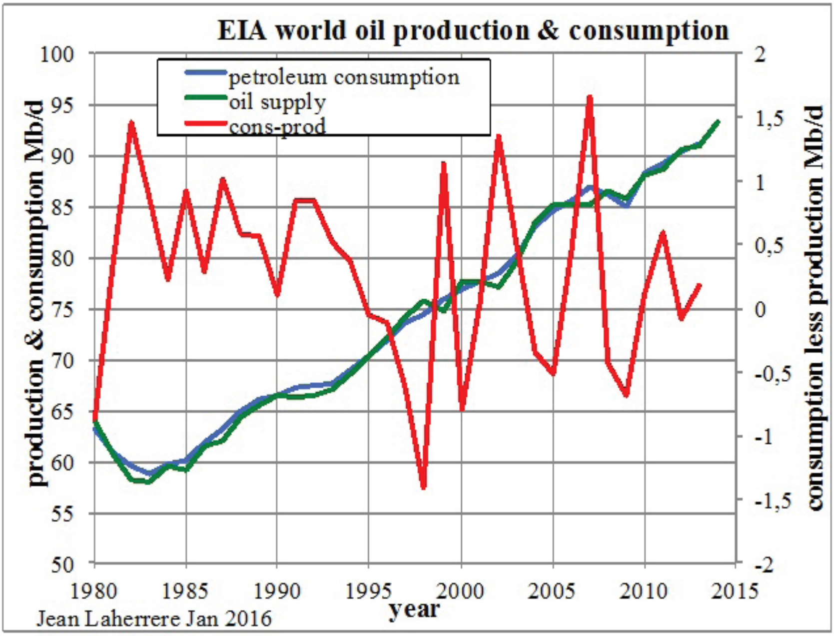

Figure 20. EIA Global All-liquids Supply and Consumption, and Difference; Data since 1980.

Notes: 'Consumption less production' data use right-hand scale.

Shows reasonably good agreement between these two datasets.

Source: J. Laherrère, from EIA data.

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including the US EIA and the BP *Stats. Review*. In case of the former, the EIA writes: "*Total Petroleum Consumption includes internal consumption, refinery fuel and loss, and bunkering. Also included, where available, is direct combustion of crude oil.*" The data issued

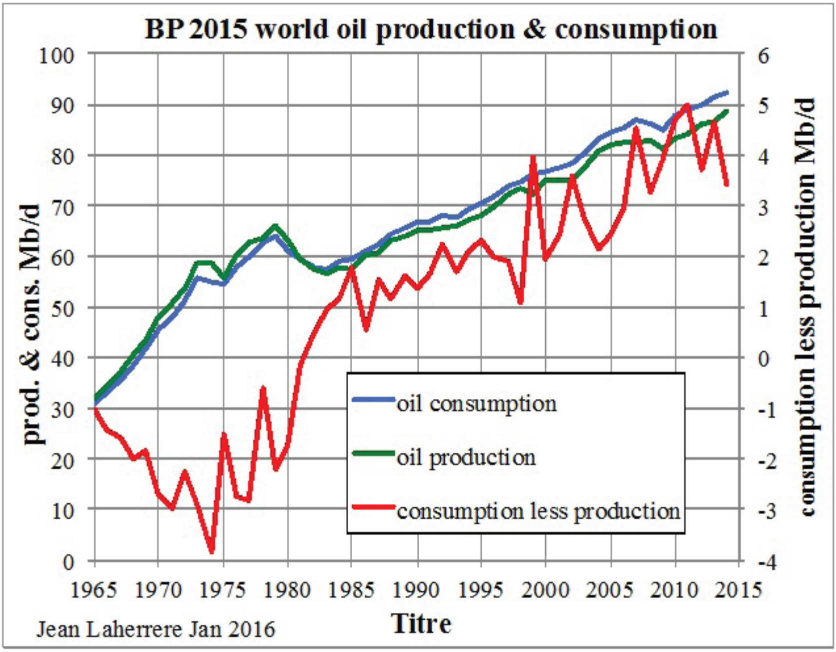

Figure 21: BP Stats. Review Oil Supply and Consumption, and Difference; Data since 1965.

Note: Over time since 1965 this difference has varied from -4 Mb/d to +5 Mb/d, giving a total range over this period of 9 Mb/d.

(For more detailed information on BP Stats. data, including caveats on their use, see the 'BP' section in Annex 6.)

Source: Jean Laherrère; from BP Statistical Review of World Energy.

by the EIA present good agreement between global production and consumption of all-liquids, as shown in Figure 20.

By contrast, the BP *Stats. Rev.* the oil production data do not include biofuels, nor CTLs & GTLs, while the oil consumption data do include these categories, resulting in a significant difference in the two datasets as indicated in Figure 21.

6. Data on Oil Discovery

Now we come to a very important topic, that of oil discovery. First we look at the rather different meaning for 'discovery' as this applies to conventional vs. non-conventional oil. Then we examine the all-important distinction between current-basis 'proved' ('1P') discovery data and the backdated 'proved-plus-probable' ('2P') data. Finally sources of 2P data are discussed, and charts from a number of different sources are presented that show the information critical to forecasting oil production, that of global backdated 2P oil discovery data vs. date.

6.1 Discovery data: Conventional oil vs. non-conventional oil

Although it is possible to forecast oil production - at least of conventional oil (i.e. normal oil in fields) - from historic production data alone (see Annex 7 in Part-2 of this paper), the only way to know for sure what the future production of this oil is likely to be, at least at a maximum, is to know how much has been discovered to-date, and is likely to be discovered in future. For conventional oil the discovery process is thus one of evolution, where the increases in geological knowledge, and the surprises and disappointments of exploration, are reflected in the discovery data.

By contrast, for forecasting production of the *non-conventional* oils the discovery process is somewhat different. Here in general the location of these oils, if not necessarily their 'sweet spots', has largely been long known, and their future production becomes primarily a function of the technology available, cost to extract, investment available, and other rate limits (such as permitting, water constraints and similar), rather than of discovery.

This difference is important when examining the oil discovery data recorded in industry databases. This is because the quantity of *conventional* oil increases over time as *new fields* are discovered; whereas, for *non-conventional* oil, the total volume likely to be recoverable has often long been known, but where the quantities of this type of oil recorded in the databases increases only as *new projects* to extract this oil are announced. When looking at the history of oil discovery in a region, this distinction (between the discovery of fields for conventional oil, and the addition of projects for non-conventional oil) needs to be borne in mind.

6.2. Discovery data: Proved (1P) vs. proved-plus-probable (2P) data

A second, and even more important distinction in terms of oil discovery data, is that between the proved ('1P') discovery data, and the proved-plus-probable ('2P') data.

1P data generally refer to producible oil reserves already in communication with a well, i.e. oil that is certain enough to count as an owner's solid assets. 2P data can include for example oil that geologists and geophysicists believe very likely to exist (e.g. by using seismic data to extrapolate the whole field from a single discovery well) but which is not yet in communication with a producible well. Experience shows that estimates of 2P reserves are generally much closer to final total production of a field than 1P reserves.

In general, analysts generate 1P 'discovery' data by calculation from apparent changes in 1P reserves combined with cumulative production to-date. But as discussed in Section 7 below, and in greater detail in Annex 5, the 1P reserves data are very misleading. This is especially so where they apply to regions and globally, and also in terms of their apparent evolution over time. As a result, apparent 1P 'discovery' data generated from public-domain sources of 1P reserves, such as the EIA or BP's *Statistical Review*, should in general be ignored.

Only 2P discovery data are generally of use when forecasting oil production, and it is this class of reserves that is discussed in the remainder of this section.

6.3. Sources of 2P oil discovery data

As mentioned earlier, for *individual fields & projects* much fairly reliable proved-plus-probable (2P) oil discovery data can come from public-domain sources such as company and government announcements.

For some *countries*, governments aggregate these 2P data over the fields and projects in their territory; and hence the country's total 2P discovery to-date can be generated by adding the country's 2P reserves (i.e., its remaining reserves) to its cumulative production to-date. Countries reporting 2P data include:

- France: BEPH reports France's remaining reserves in Mt, where these are 2P data, being close to the equivalent IHS Energy data given in Mb; and very different from the 1P reserves data reported by the EIA, or in the in *OGJ* or *World Oil*; as shown in Figure 22.

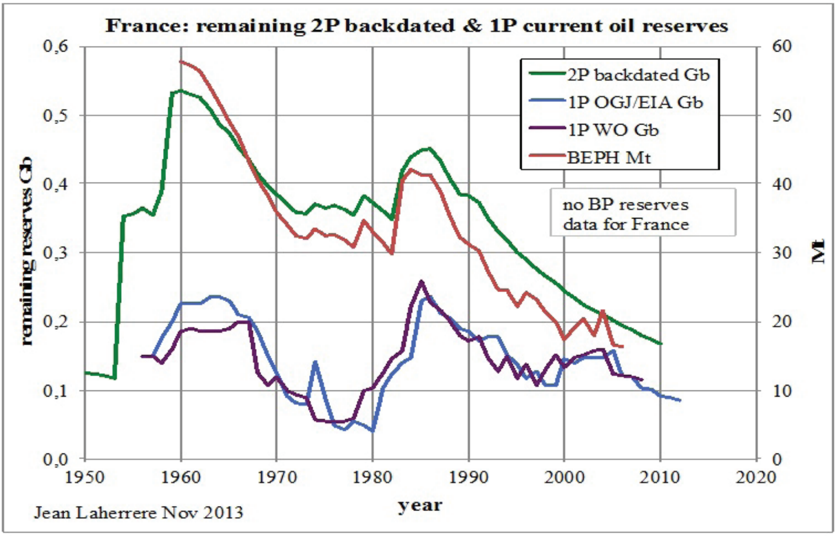

Figure 22. Four sources of data on France's Oil Reserves.
Legend:
- 2P backdated Gb: IHS Energy data on 2P reserves, given in Gb.
- BEPH Mt: France's BEPH data on reserves, given in Mt, where these need to be multiplied by 7.33 and divided by 1000 to convert to Gb.
- 1P OGJ/EIA Gb: 1P reserves data given in Gb by the Oil & Gas Journal and the EIA.
- 1P WO Gb: 1P reserves data given in GB by the journal World Oil.

- Norway: The NPD, for reserves by field, reports the operator values, and these are required to be ~2P. (Strictly, the oil companies' data reflect NPV valuations of development plans based on mean reserves, where the latter are close to 2P.) Note that early Norwegian reports of aggregate reserves seem to have reported 1P, so caution is needed if using past reports to examine the evolution of reserves over time.)

- Denmark reports field data in e.g. http://www.ens.dk/sites/ens.dk/files/energistyrelsen/Nyheder/2014/oil_and_gas_production_in_denmark_2013_uk.pdf.

These data are 2P, and are close to the IHS Energy backdated 2P data.

- The UK's Ministry for Business, Energy & Industrial Strategy (formerly DECC) reports proven (1P) field reserves (but aggregates these by direct summation, which gives an incorrect total); and also probable reserves. When proven and probable are summed to give 2P reserves, these can be aggregated to give a correct total. Possible reserves are also reported.

- US: Aggregated 2P discovery data are available from a limited number of government departments, such as the US MMS (now BOEM & BSEE) for US offshore data; and from some US states (such as California).

- Canada: 2P data are available from industry associations, such as Canada's CAPP.

(For additional discussion of some of these data, including data problems, see entries for the specific organisations in Annex 6.)

However, for most countries, and globally, to access the relevant 2P discovery data for forecasting production it is necessary to turn in general to the commercial data providers.

As previously noted, it takes a great deal of work for these companies to 'scout out' and then check and assemble the 2P field and project data into reliable totals for basins, countries, and globally. For this reason, 2P data on oil discovery for most regions and globally from the commercial databases are usually expensive, and often very expensive. These companies include Globalshift Ltd., IHS Energy, Nehring Associates, Rystad Energy and Wood Mackenzie, among others. In addition, by-country and global 2P discovery data can obtained from publications by those with access to these data, including Laherrère, Campbell and a few others.

However, it is important to recognise that even the 2P data in industry commercial databases are questionable for some countries and regions. This is illustrated below in Figures 25 and 26, and discussed in more detail in Annex 6.

6.4 Charts of 2P global oil discovery data

To see the importance of the discovery data, in this section we first present a chart showing the history of global oil-plus-gas discovery in terms of the backdated 2P data, and then nine charts that give these data for discovery of oil only. The first five charts show cumulative data, and the others annual.

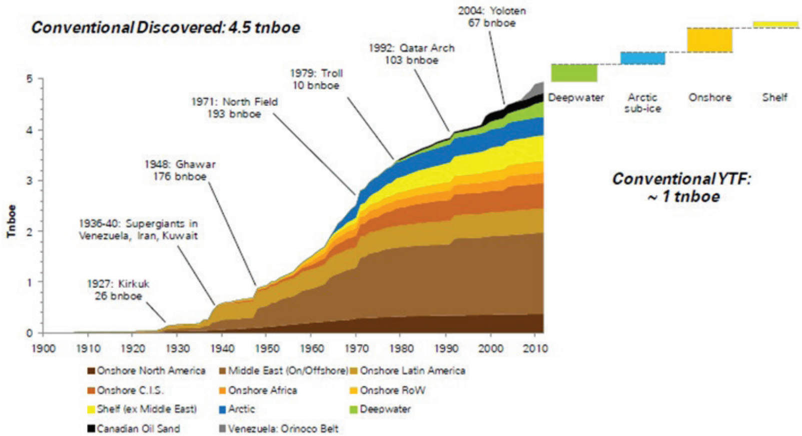

Figure 23. Global Discovered Oil plus Gas Resource, and Yet-to-Find, by Discovery Category; 1900 - ~2012.

Notes: - See the presentation for discussion of the oil and gas categories covered, and where 'light-tight' oil is in the 'Onshore' category

- Excludes consideration of oil from kerogen, GTLs and CTLs, and biomass.

Source: Presentation 'Future Trends in Global Oil and Gas Exploration' by Dr. Michael C. Daly, Executive Vice President Exploration, BP plc, given at Imperial College, University of London, 23 September 2013.

6.4.1 Long-term cumulative global 2P oil discovery data

The first chart in this series, Figure 23, is from a BP presentation that showed the evolution of global discovery of all-oil (i.e., conventional and non-conventional) plus all-gas since 1900. The chart also shows the author's view of the likely quantities of all-oil-plus-all-gas yet-to-find by category. The data are from IHS Energy, except for the US and Canada, where they are from the EIA and CAPP.

As Figure 23 shows, the inflection point in global discovery of oil-plus-gas was in the mid-1960s, after which discovery started to tail off, though recall the caveat given earlier about the difference in discovery of conventional oil in *fields* vs. that of announcement of non-conventional oil in *projects*. For consideration of the total discovered, and likely to be discovered in future, see Section 11 below on URR values.

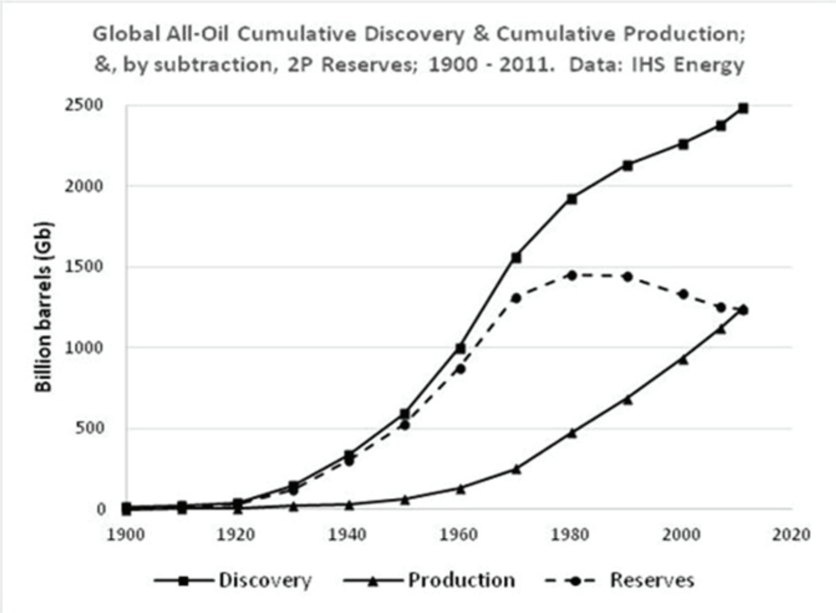

Figure 24. IHS Energy Data for Cumulative 2P Backdated Oil Discovery, and Cumulative Oil Production (also hence 2P Reserves by subtraction), 1900-2011. Notes:

- The plot shows IHS Energy 'Liquids' data, stated to include: "crude oil, condensate, NGLs, liquefied petroleum gas, heavy oil and syncrude". The data thus include light-tight oil, and oil from oil sands and Orinoco oil, but exclude GTLs, CTLs, biomass, and refinery gain.
- Data are 2P, except for the US and Canada non-frontier areas, where the data are proved ('1P') data. The 2P data are backdated, in that they reflect information available to the IHS Energy as of 2007 (for the discovery curve), and to 2011 (for the final discovery data point). Reserves are calculated here (as done also by IHS Energy) by subtracting cumulative production from cumulative discovery.
- IHS Energy data are for oil in fields for conventional oil; and as announced in projects for non-conventional oils. The 'up-tick' in global discovery of this 'all-oil' visible from about the year 2000 (and hence the slowing in the fall-off of 2P reserves) is due in part to increasing inclusion of data for tar sands projects, and subsequently for US shale (light-tight) oil projects. Data are hence largely for conventional oil up until about the year 2000, after which significant amounts of tar sands and Orinoco projects were included, and most recently also data for 'light-tight' oil projects.

Source: The data are from the IHS 'PEPS' dataset, and plot is generated by reading data at 10-year intervals from Figure 7 of Miller and Sorrell (2014) for cumulative discovery from 1900 to 2007, and from the corresponding Figure 3 for cumulative production over the same period. Included in this plot are the data for end-2011 as given in the text of the Miller and Sorrell paper.

(Note that Figure 8 of that paper notes that these discovery data are potentially somewhat misleading as they include different amounts of reserve growth for fields discovered many decades ago compared to more recent fields. 'Reserves growth' is an important topic, and is discussed briefly in Section 8, below.)

The second chart, Figure 24, also gives IHS Energy global discovery data since 1900, but here for only all-oil (i.e., excluding gas). The chart also gives the corresponding production data, allowing the evolution of global all-oil 2P reserves to be calculated, as shown.

A great deal can be learned from Figure 24: In terms of the backdated data for *conventional* oil (i.e. the data shown on the chart up to about the year 2000; after which data on non-conventional oil became significant):

- The rate of *discovery* rose rapidly from 1900, but peaked around 1965 and has been in decline since.

- For most of this period the total quantity of oil discovered raced well ahead of that produced, putting large quantities of 2P oil reserves 'in the bank'. This oil 'in the bank' increased until about 1980, but at this date the rate of production caught up with the rate of discovery of oil in new fields, and hence subsequently this quantity of 2P reserves 'in the bank' has declined.

- As noted above, after about the year 2000 much of the oil shown as 'discovered' represents addition of *non-conventional* oil projects to the database. On this basis, the long-term 'reasonable-extrapolation' URR for global *conventional oil* based on the discovery trend looks to be about 2500 Gb or so.

- As the chart then shows, by about now the quantity of global conventional oil produced has reached about half this projected URR; i.e., the point at which - on a simple 'mid-point' rule - one would expect global production of this oil to peak, and then decline.

The next two charts of oil global 2P discovery history, Figures 27 and 28, are from Laherrère and Campbell respectively. A key aspect of these charts is that though they are based on commercial 2P oil discovery datasets, the data have been adjusted in light of the authors' judgements; primarily by reducing oil discovery volumes for some categories of oil.

We give three examples of such adjustment in the case of the 2P oil discovery data presented by Laherrère in Figure 27:

- Firstly to obtain global discovery data for crude-plus-condensate only, from the IHS end-2010 field discovery data the extra-heavy oils are excluded, where this includes subtracting early Orinoco discoveries.

- Secondly the discovery data for fields in FSU countries are multiplied by 0.7. This reflects Laherrère's judgement - and that of others - that these data are typically 'ABC1' field data, and where 0.7 is the average ratio of 2P reserves vs. the ABC1 reserves reported by Gazprom; Figure 25. (Note that slightly different adjustment ratios apply to gas and condensate data.)

- Thirdly, OPEC 2P reserves are reduced by some 300 Gb in total. This in part reflects a statement at the London 2007 'Oil and Money' conference by Sadad al-Husseini, President of Husseini Energy Consultancy and former Executive Vice President of Saudi Aramco's upstream operations, that 300 Gb of OPEC oil reserves should properly be classed as 'speculative resources'. This view is supported by the evolution over time of some OPEC 2P reserves data from IHS. For

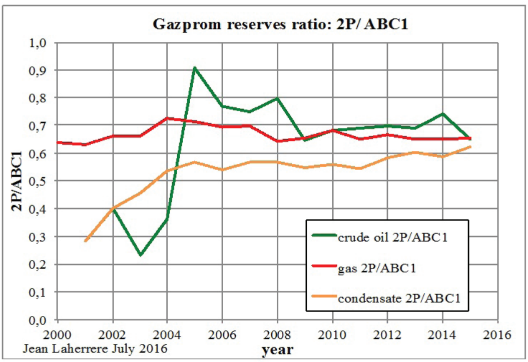

Figure 25. Gazprom Ratios of 2P Reserves vs. ABC1 Reserves, vs. Date. Source: J. Laherrère.

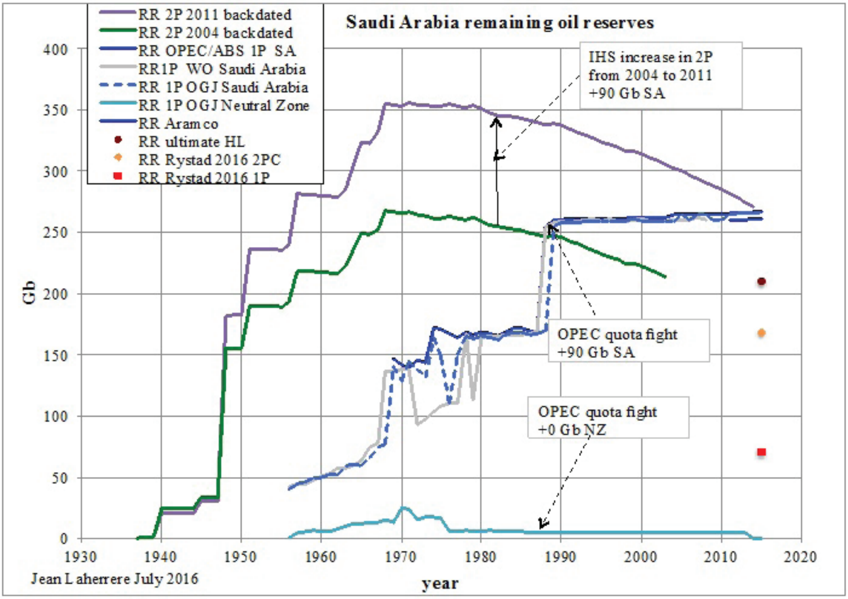

Figure 26. Evolution of Saudi Arabian 1P and 2P Reserves data; Various sources.

Legend:

- 'RR': Remaining reserves; i.e. reserves as of this date.
- 2P 2011 backdated: Saudi Arabian (ex Neutral Zone) backdated 2P data for reserves as reported in the IHS 2011 survey.
- 2P 2004 backdated: Ditto, as reported in the IHS 2004 survey.
- OPEC/ABS 1P SA: Saudi Arabian 1P reserves as reported by OPEC.
- 1P WO Saudi Arabia: Ditto, as reported by World Oil.
- 1P OGJ Saudi Arabia: Ditto, as reported by Oil & Gas Journal.
- 1P OGJ Neutral Zone: Neutral Zone 1P reserves as reported by Oil & Gas Journal.
- Aramco: Saudi Arabian 1P reserves as reported by Aramco.
- ultimate HL: Saudi Arabia reserves computed by subtracting cumulative production to-date from a URR for Saudi Arabian oil estimated by 'Hubbert linearisation' of the production data.
- Rystad 2016 2PC: Saudi Arabia reserves as given by the '2PC' value estimated by Rystad Energy in 2016. ('2PC' indicates 2P reserves for fields in production plus those discovered but not yet in production, see Table 1.)
- Rystad 2016 1P: Ditto, as given by the '1P' value estimated by Rystad Energy in 2016; see Table 1.

Source: J. Laherrère, from sources listed.

example, as shown in Figure 26, Saudi Arabia 2P reserves increased by ~90 Gb from the data in their 2004 survey to that in the 2011 survey; and where some analysts have suggested the company may have revised their data to match those of Aramco.

The rather dramatic items to note from Figure 26 are:

- As mentioned, IHS backdated 2P reserves data for Saudi Arabia (less the Neutral Zone) jumped 90 Gb between the company's 2004 and 2011 survey data. As the plot shows, the bulk of these increases were ascribed to revisions to the size of the early super-giant discoveries (Ghawar in 1948; and discoveries in 1951, and ~1957; and in a number of large discoveries up to ~1968). There was much less upward revision in the more recent field-size estimates.

- In the period to 1980, there were significant differences in *1P reserves* data for Saudi Arabia as given by Aramco, OPEC, *World Oil* and the *Oil and Gas Journal*; but since that date the 1P data have been in close agreement.

- These 1P data for Saudi Arabia exhibit the well-known ~90 Gb upward step-change in 1988, due to OPEC 'quota wars'. (This is in contrast to no 'quota wars' step-change in the Neutral Zone 1P data.)

- These 1P data also show an implausible period of essentially static values since 1988, despite ~80 Gb having been produced over this period.

- Today Saudi Arabian *1P* reserves stand at ~270 Gb; and hence closely match the 2P reserves as given by the IHS 2011 data when adjusted for production since 2011.

- This figure is about 100 Gb larger than the current 2P value of ~170 Gb that would expected from the IHS 2004 data if combined with cumulative production since that date. Moreover this value, of ~170 Gb, matches Rystad's current '2PC' estimate, of 168 Gb, for the country's 2P reserves of all discovered fields, see Table 1.

- If one judges this ~170 Gb estimate of reserves to be the more accurate, then an estimate of Saudi Arabia's URR for conventional oil can be generated. This is done by adding these reserves to the country's cumulative production to date of ~140

Gb, plus an allowance for yet-to-find (calculated, for example, by subtracting the '2PC' value from the '2PCX' value in Table 1). This gives a URR for Saudi Arabia's conventional oil of ~365

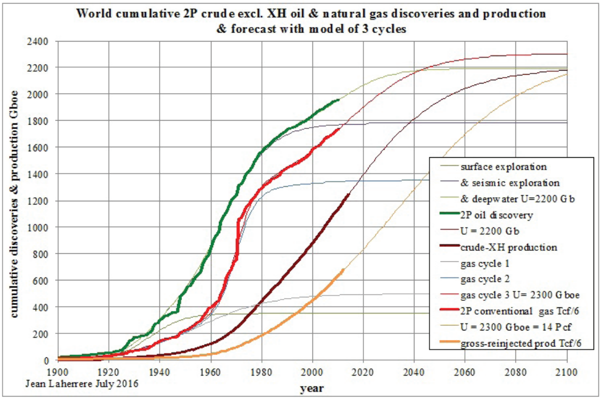

Figure 27. Laherrère data for Global Cumulative 2P Backdated Oil Discovery 1900 - 2010, and forecast to 2100; Cumulative Oil Production, 1900 – 2013, and forecast to 2100.

(Also shown are the corresponding discovery and production data for gas.)

- Leftmost line: Laherrère's judgement of 'most probable' backdated 2P cumulative global discovery data for crude oil plus condensate, less extra heavy oil (the latter mainly Athabasca tar sands and Orinoco oil), and not including NGLs.
- Next left line: Corresponding data for gas, calculated as Tcf/6.
- Next leftmost line: Cumulative global production of crude oil less extra heavy oil and NGLs.
- Rightmost line: Cumulative global production of gas, Tcf/6.

Laherrère writes: 'The 2P discovery data reflect data from industry 'scout' sources, but reduced by: 300 Gb to allow for overstatement of the OPEC Middle East original reserves data (as confirmed by Sadad Al-Husseini, former VP Aramco, 2007 Oil & Money conference London); by 30% of the FSU data (~100 Gb) to allow for the datasets ABC1 holding probably closer to 3P than 2P data (as indicated by field decline plots, and by Gazprom audits in annual reports); and by 200 Gb to allow for Orinoco 2P discovery data reflecting non-conventional oil.'

Note: On the gas data shown, the simple 'mid-point' peak of global conventional gas production would be expected around 2025.

Source: J. Laherrère: Underlying data: Oil industry 2P 'scout' data, plus judgement.

Gb. This estimate in turn matches quite well that obtained by addition of the country's cumulative production to-date with the reserves obtained from a 'Hubbert linearisation' of production (as given in Figure 26 of ~210 Gb); generating an estimated URR of ~350Gb.

- Finally, if the 'mid-point' rule is combined with the ~365 Gb estimate of URR, the country's peak in its production of conventional oil is expected about 2025. This peak may be somewhat delayed by the long flat nature of the country's field production profiles (which delays peak, though speeds subsequent decline, in a simple regional 'field summation' model), and by the likely increased application of EOR.

Based on the considerations set out above, Figure 27 shows the resulting chart of global cumulative 2P oil discovery, and also production, since 1900 as generated by Laherrère. The data are for crude oil, but exclude NGLs and extra-heavy oils (the latter mainly oil sands and Orinoco oil). Also shown are the global cumulative discovery and production data for gas.

From Figure 27 we can see for conventional oil (taken here as crude oil less extra-heavies, and including Laherrère's judgement on the reductions needed to the discovery data) that by 2010 some 1950 Gb or so had been discovered. This leads in turn to an estimated 'reasonable-extrapolation' URR based on the discovery trend for this class of oil of about 2200 Gb (as opposed to the estimate based on the IHS Energy data in Figure 24 of ~2500 Gb). With Figure 27 showing global cumulative production of this oil as having reached about 1200 Gb by 2010, its global production peak would - from the simple 'mid-point' rule - be expected to be already passed.

Figure 28 gives a third, roughly comparable, chart. Here the global cumulative backdated 2P oil discovery data are from Campbell, and are for his definition of '*Regular conventional*' oil; see notes below the chart.

Figure 28 indicates that Campbell's view of the global URR for '*Regular Conventional*' oil, based in his model on the summation of 'reasonable-extrapolation' discovery trend URR's for individual oil

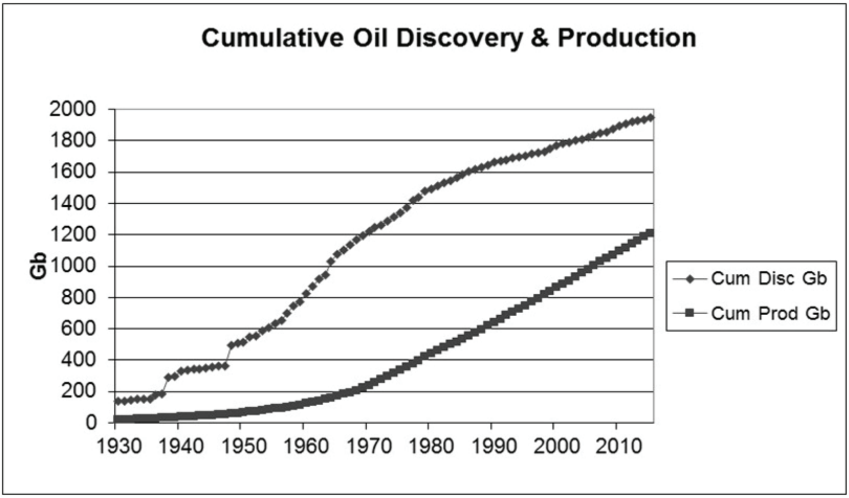

Figure 28. Cumulative Global 2P Discovery & Production of 'Regular Conventional' Oil.

Notes: Campbell's 'Regular conventional oil' is defined as all-oil less:
- Polar oil (north of 66.6° N),
- Deepwater (>500 m water depth);
- All heavy oils (< 17.5 °API), thus including oil sands and Orinoco oil,
- NGLs.

Underlying data are to 2010.

See the entry for Campbell data in Annex 6.

For details of Campbell's oil forecast model, see Campbell (2015).

Source: Campbell's Atlas of Oil & Gas Depletion, Springer, 2013.

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producing countries plus extensive geological knowledge, is about 2000 Gb.

Since the chart shows global production of this oil to have reached ~1100 Gb by 2010, it is no surprise that Campbell's model assesses the global production peak of this oil now to be passed, being reached in 2004.

As explained, the main reasons for the differences between Figures 23, 24, 27 and 28 are primarily due to the inclusion of different categories of liquids (particularly NGLs and the extra-heavy oils, including Canadian tar sands and Orinoco oil), and also to both Laherrère's and Campbell's views of the need to reduce the size of industry 2P discovery volumes for the FSU and for some Middle East countries, as set out above.

However, despite these differences all four Figures indicate that the rate of global discovery of *conventional oil* peaked about the mid-1960s; and hence, given the production data, that the global 2P *reserves* of this oil have been in decline since about 1980.

In a somewhat similar chart we can look at global data on the *number of oil fields* discovered. Figure 29, like Figure 27, is from Laherrère, and

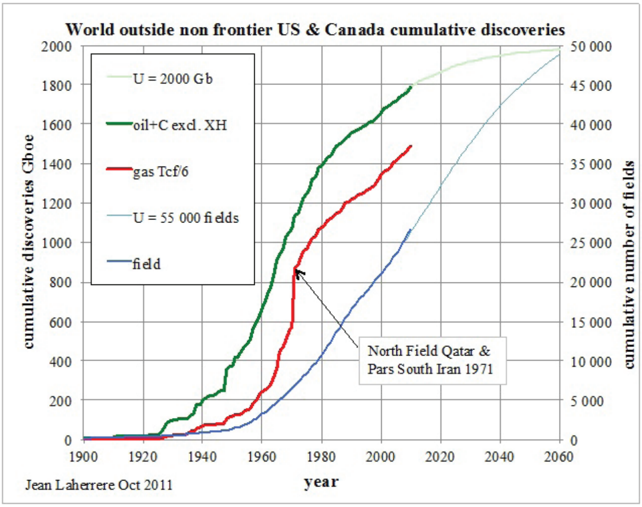

Figure 29. Global data, *excluding US & Canadian non-frontier areas*: Cumulative discovery of crude oil less extra-heavy oils; Cumulative discovery of gas; and Cumulative discovery of oil plus gas fields; 1900-2010.

Legend:

- U = 2000 Gb: Forecast cumulative 2P discovery curve of global crude oil plus condensate less extra-heavy oils, if the URR for this category of oil is 2000 Gb.

- oil+C excl. XH: Historical cumulative 2P discovery curve of global crude oil plus condensate less extra-heavy oils,

- gas Tcf/6: Historical cumulative 2P discovery curve of global gas, where this is converted to Gboe by dividing the Tcf discovered by 6.

- U = 55 000 fields (right-hand scale): Forecast cumulative curve of the number of oil and gas fields combined (excluding US & Canadian non-frontier areas) that will be discovered, if the 'ultimate' number of these fields totals 55 000.

- field (right-hand scale): Historical data on cumulative discovery curve of the number of oil and gas fields combined (excluding US & Canadian non-frontier areas) that have been discovered.

Notes:

- For gas discovery, Laherrère here combines discovery of Qatar's North Field with Iran's South Pars. As he writes: "The [apparent] peak of [global] gas discovery in 1991 as shown in IHS Energy data [Figure 30, below] is due to the condensate of the South Pars field in Iran. But this is the northern part of the North Dome in Qatar discovered in 1971; thus the IHS data are [somewhat misleading] as everyone [in the industry] knew of the extension in Iran, but that Iran waited to 1991 to drill this due to a lack of market."
- US & Canada non-frontier regions add over 50 000 *additional* fields, both regions having been very extensively drilled. (In the US this was partly simply because of the long-history of oil exploration, and slow accretion of sound knowledge of where oil was likely to be found; but also due to land rights that give ownership of the minerals beneath.)

Source: J. Laherrère; from industry data sources.

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again is based on backdated oil industry 'scout' 2P data, but here excludes data from US and Canadian non-frontier regions; and includes data on the corresponding number of oil plus gas fields discovered.

As Figure 29 shows, the cumulative number of crude plus condensate, less extra-heavy oil fields, and gas fields combined discovered globally outside of US & Canada non-frontier areas up to 2010 reached some 26 000, and contained some 1750 Gb of this class oil and 8700 Tcf of gas. Reasonable extrapolation, including geological knowledge, indicates that a likely 'ultimate' of about 55 000 fields will be discovered; with, for this class of oil, containing some 2000 Gb. This URR can be compared to Laherrère's anticipated global URR for this class of oil, but based on full global data including US and Canadian non-frontier areas as shown in Figure 27, of about 2200 Gb.

6.4.2 Recent annual global 2P oil discovery data

Now we turn from long-term backdated cumulative 2P data on oil discovery to more recent 2P discovery data, and where these are shown on an annual basis.

Figure 30 gives annual data for 1984 to 2014 from IHS Energy for 2P discovery of both global oil and gas; and Figure 31 gives slightly more recent IHS Energy data for oil and gas discovery (outside of the US) up to 2015.

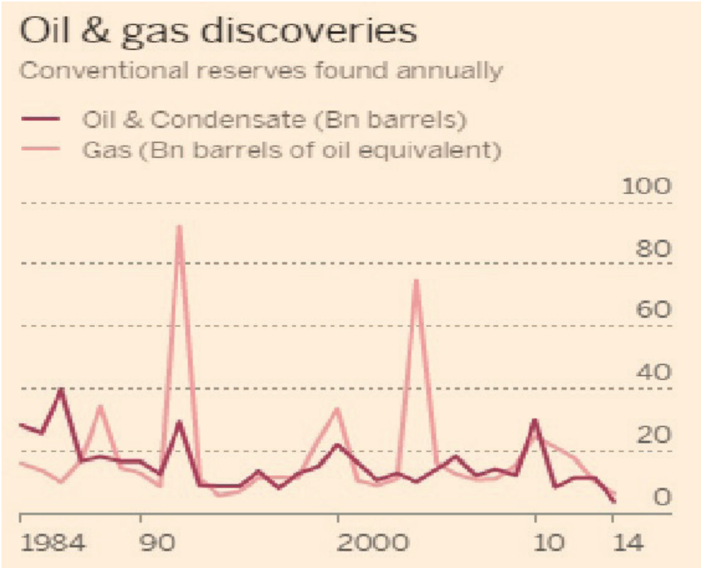

Figure 30. IHS Energy data on Annual Discoveries of Conventional Oil plus Condensate, and also of Gas, 1984 – 2014.

(We apologise for lack of definition of this plot.)

See note to Figure 29 on the need to backdate the 1991 gas discovery.
Source: J. Laherrère, from IHS Energy.

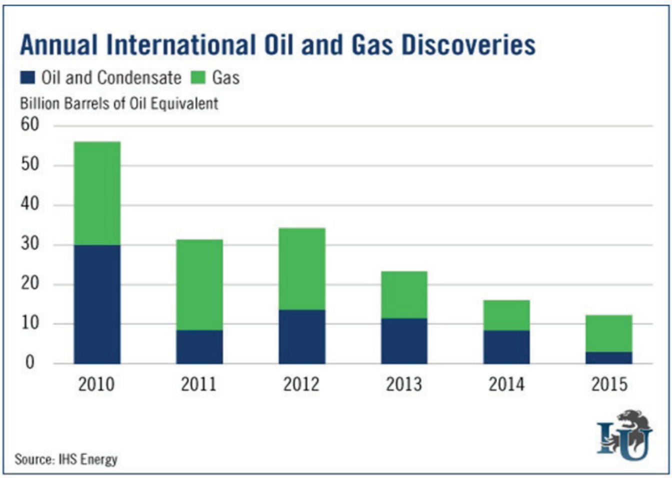

Figure 31. IHS Energy data on International (i.e., outside the US) Annual 2P Discoveries of Oil plus Condensate, and of Gas, 2010 – 2015.

Figure 32 shows the corresponding data from Rystad Energy for 2000 to 2015.

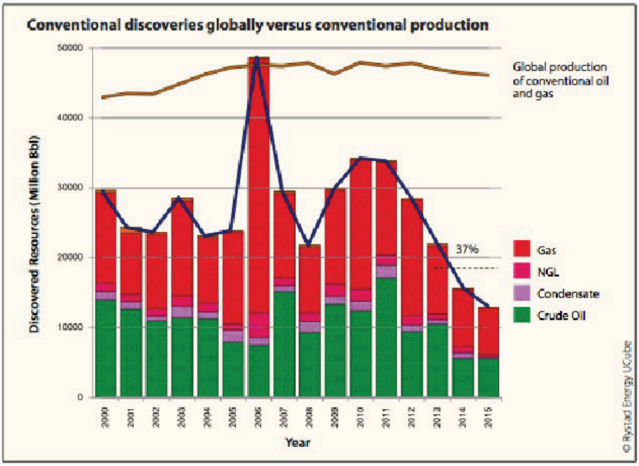

Figure 32. Rystad Energy data on Annual Discoveries of Conventional Oil and Gas, by Category, 2000 – 2015.
Source: Article by Halfdan Carstens in the magazine: GEOExPro, original data: Rystad Energy.

And Figure 33 shows data from Wood Mackenzie, here for conventional oil only, covering the period 1948 (the discovery of Ghawar) to part of 2016.

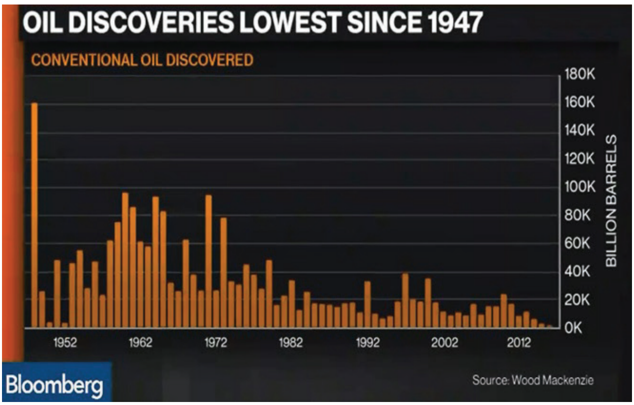

Figure 33: Wood Mackenzie data on Annual Discoveries of Conventional Oil, 1948 - 2016 (part).
Source: Bloomberg, accrediting Wood Mackenzie.

As can be seen, the 2P discovery data from all these three sources (IHS, Rystad and Wood Mackenzie) are roughly comparable in volume terms, if allowance is made for differences in the discovery dates of fields (or equivalently, of announcement dates of projects).

Importantly, as Figure 32 - and also the charts of long-term discovery, given earlier - show, over recent years the discovery of oil plus gas combined have been less, and often considerable less, than production. Note that these are current data, so that scope for increasing the size of these discoveries via price- or technology-driven 'reserves growth' is not included. But even so, as Carstens notes in Figure 32, "*In the long run this* [situation] *will certainly result in a higher oil price.*"

To indicate this important comparison of annual 2P discovery vs. production over a longer timeframe, Figure 34 is a composite of the data in Figures 27, 30 and 32.

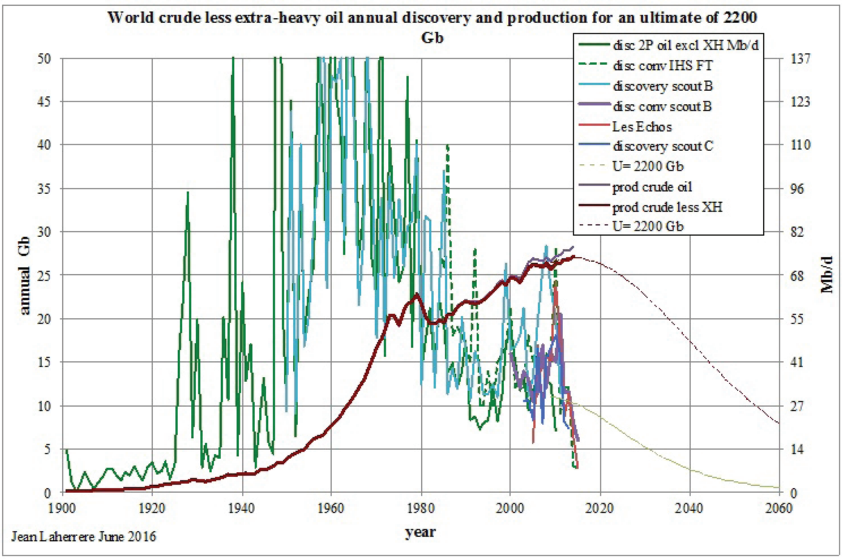

Figure 34. Summary of Annual Data on Global Backdated 2P Oil Discovery, and Production, of 'Conventional Oil' (as variously defined), and of 'All-oil', from different Data Sources, 1900 - 2015.

Legend:

- disc. 2P oil excl. XH Mb/d: 2P data on the discovery of crude oil plus condensate less extra-heavy oils, from data-provider ('scout') company 'A'.

- disc. conv. IHS FT: IHS Energy data as reported in the *Financial Times*.
- discovery scout B: 2P data on the discovery of 'all-oil' from data-provider ('scout') company 'B'.
- disc. conv. scout B: : 2P data on the discovery of conventional oil from data-provider ('scout') company 'B'.
- Les Echos: As reported in the French newspaper *Les Echos*.
- discovery scout C: 2P data on the discovery of 'all-oil' from data-provider ('scout') company 'C'.
- U= 2200 Gb: Projection by the author of the 2P *discovery* of crude oil plus condensate less extra-heavy oils, based on an assumed URR for this class of oil of 2200 Gb.
- prod crude oil: Production data of global crude oil plus condensate.
- prod crude less XH: Production data of global crude oil plus condensate less the extra-heavy oils.
- U= 2200 Gb: Projection by the author of the *production* of crude oil plus condensate less extra-heavy oils based on an assumed URR for this class of oil of 2200 Gb.

Notes: - This Figure is a composite of the data in Figures 27, 30 and 32.
- Figure 27 data exclude extra-heavy oils; while Figure 30 and 32 data are specified as conventional oil, but where this definition is likely to differ between sources.

Sources: As given in Figures 27, 30 and 32.

As can be seen from Figure 34, and as discussed earlier, the annual rate of discovery of *conventional* oil - as given by the backdated oil industry 2P data - generally increased to about 1965, and has been in variable, but fairly steady, decline since then.

From at least 1900 to about 1980 the annual rate of discovery ran well ahead of annual production, putting 2P reserves 'in the bank'. By contrast, for most of the years since 1980 production has exceeded discovery (in terms of oil in new fields, and announcements of oil in new projects), and hence the global 2P reserves have declined.

Note that in examining the above 2P discovery plots, two important caveats need to be borne in mind:

The first is that the data shown are *backdated*, i.e., reflect knowledge of the field sizes as of the date of publication of these data. If instead *current-basis* 2P data were shown, the shape of the global cumulative discovery curve would be somewhat different. But: (a) such current-basis data going back in time are generally unavailable;

and where available, hard to retrieve as print-version archival sets of the discovery data need to be accessed; and (b) the difference in shape of the two global cumulative discovery curves (current-basis vs. backdated) is not likely to be so very different; see the discussion in Bentley (2016a).

The second important caveat is that the discovery data shown do not include allowance for *future 'true 2P reserves growth'*; i.e. for the expected future changes (in the past, usually gains) in existing field volumes due to advances in technology or a higher oil price. The *theoretical potential* for such reserves growth in conventional oil fields is large, but a variety of considerations says the actual reserves growth that will occur is probably not so very great, see Section 8 below.

7. Data on Oil Reserves

In terms of understanding future oil production, as with the discovery data, for the *reserves* data also it is essential to be aware the crucial distinction between 1P and 2P data. This distinction is of particular relevance where field data have been aggregated, for example to provide a total for a region (such as country), or globally.

7.1 Generation of 1P reserves

The process for generating *1P oil reserves* has many problems, and has led to extraordinarily misleading data. There are five main factors contributing to this data miasma, as follows:

(i). SEC rules

In the early days of oil exploration wild claims were made for the volume of oil in fields, often caused by ignorance of the field itself, but also commercial pressures to exaggerate field sizes to attract investors. In time, in the US the Securities and Exchange Commission (SEC) stepped in and mandated sound conservative estimating procedures, in particular that any reserves declared had to be 'in communication' in production terms with a drilled - or imminently planned - well. Naturally such conservative estimates on field size increased over time - at least for large fields - as they were 'drilled up' during their development. In the US and Canada such growth in apparent field size, as recorded by increases in declared proved reserves has been up to 10-fold or more, with 6 and 9-fold increases being the norm for older onshore fields in, respectively, the US and Western Canada.

Today only a small minority of total world oil reserves are reported under SEC rules, those under the control of commercial oil companies, and even here there is sometimes a temptation for an oil company to report closer to 2P reserves, rather than 1P; this having lost at least one CEO of an oil multinational his job.

It is important to recognise that over time the conservative proved (1P) reserves volumes grow naturally towards the more likely proved-plus-probable (2P) reserves volumes, as the full field infrastructure and extraction regimes are put in place, and any potential uncertainty on the extractable oil volume remaining in a field steadily decreases. Thus late in a field's life it is normal that its 1P and 2P reserves estimates become essentially the same.

(ii). Aggregation

The second problem with 1P reserves data is where they have been aggregated. 1P reserves are conservative values (sometimes judged as 'P90', that is, having a 90% chance of being exceeded), but where simple arithmetic addition of such numbers significantly underestimates the totals at the probability level specified. This is indicated in Figure 35 which shows that only the arithmetic sum of a mean value is correct; addition of P90 (1P) values results in a large underestimation and addition of P10 (3P) values in a large overestimation.

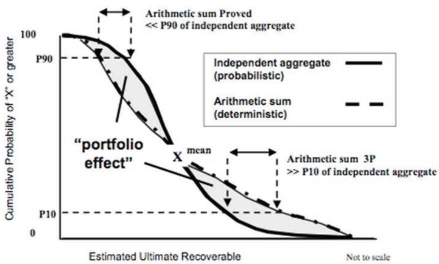

Figure 35. The error arithmetically adding probabilistic data: aggregation of proved reserves underestimates the total reserves for a region.

See: Laherrère J.H.: '*Advice from an old geologist-geophysicist on how to understand Nature*'. Presentation to Statoil, Oslo, 14 August 2008. http://aspofrance.viabloga.com/files/JL_Statoil08_long.pdf

(iii). Government reporting

A third problem with 1P oil reserves data has to do with their handling by governments. Even governments that are good providers of data have rules – often not fully clear – on what they report in national documents. The UK, for example, over many years has published aggregate proved oil reserves data that have consistently been about half the volumes recorded in industry datasets for 2P data. Certainly in the early years the 1P data would be expected to be lower than 2P, but now with most fields rather empty the data should not be so far apart. For a comparison of the UK 1P with 2P data (given in discovery rather than reserves terms) see Figure 10 in Sorrell and Speirs (2014).

The reason for these recent UK 1P reserves still being half the 2P data is not clear; it may be due to which discovered fields have been sanctioned, or to a significant number of currently ‘fallow’ fields recorded in the industry data. But the fact that for more than two decades the UK reported a consistent ‘five years’ worth of oil reserves’ confused both the government itself and many analysts, and led to incorrect and widely-reported conclusions being drawn on the ability of technology to ‘replace’ reserves.

(iv). OPEC reporting of 1P reserves

In volume terms, a far more serious case of misreporting of ‘proved’ oil reserves are those for some OPEC counties. These reserves are un-audited, and their volume is specified by government edict. This aspect of reserves reporting, termed ‘quota wars’, has been fairly widely discussed, and is covered in greater depth in Annex 5. It represents a possible over-reporting of global oil reserves, compared to the ‘true’ 2P reserves, of up to perhaps 300 Gb.

(v). ‘Static’ reserves

Finally in this list of problems with 1P oil reserves data is the extraordinary fact that for many countries these data do not change year-on-year. This applies in many cases, but particularly long runs of static or nearly-static reserves data are reported by some OPEC countries, and hence reported in turn by public-domain sources; see the table on this in Annex 5. Not only is this a further indication of how unreliable are the 1P reserves data, but adds another reason (in addition to their initial conservatism) as to why *apparent changes* in 1P reserves are even more misleading than the data themselves.

7.2 Sources of 1P oil reserves data

As indicated, 1P oil reserves data for *fields and projects*, if under the control of commercial oil companies, are generally reported under SEC rules (although these companies are now permitted to also report 2P data if they so decide). But for *aggregated* 1P reserves data for countries and globally, these data are those given in public domain sources such as the EIA data listings, the *Oil & Gas Journal*, *World Oil*, or the BP *Stats. Review*.

Figure 36 compares the evolution of global 1P reserves data vs. date, as given by five public-domain sources.

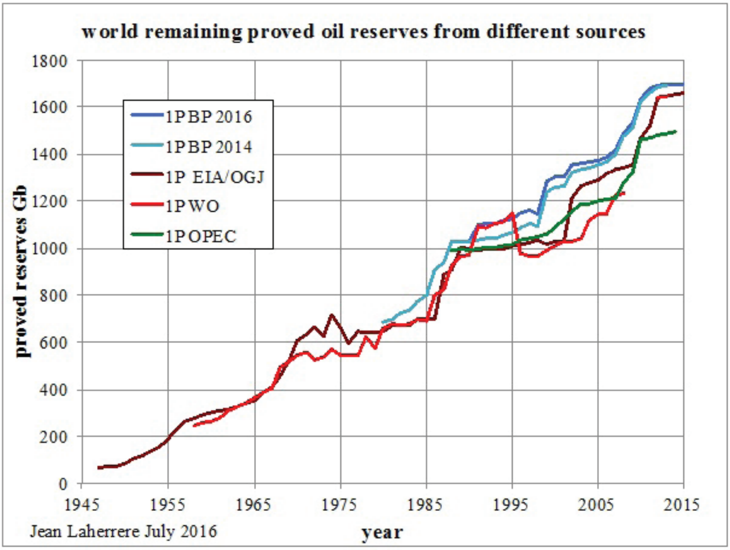

Figure 36. Comparison of Global Proved ('1P') Oil Reserves data from different Public-domain sources; Current range ~1500 Gb to ~1700 Gb.

Legend:

- 1P BP 2016: Global proved oil reserves as reported in BP *Stats. Review* 2015
- 1P BP 2014: ditto, BP *Stats. Rev.* 2014 edition.
- 1P EIA /OGJ: ditto, as reported by the EIA; and *Oil & Gas Journal.*
- World Oil: ditto, by the journal *World Oil.*
- OPEC: ditto, by OPEC.

Chart from J. Laherrère.

7.3 Generation of 2P reserves

In stark contrast to 1P oil reserves, the process for generating 2P reserves is relatively straightforward, as follows:

For each field or non-conventional oil project the commercial 'scout' databases give the field or project's expected initial reserves (or, equivalently, its ultimately recoverable reserves, URR; or estimated ultimate recovery, EUR). These data give an estimate of total production from the start of production to the point where it is expected the field or project will be abandoned. In some databases, IHS Energy for example, certainly in the past, these initial reserves estimates included reasonable allowance for the use of improved technology over time, and also a somewhat higher oil price. Then, since the same databases also carry the production history of each field and project, the corresponding current '2P' reserves (i.e. remaining reserves) are calculated as initial reserves less cumulative production to-date. In addition, because these reserves data are approximately mean-value estimates, they can be arithmetically summed to give substantially correct totals for regions and globally (but see also Capen, 1996).

However, even with the 2P reserves data a number of significant cautions are needed:

- Initial *announcements* of anticipated field or project volumes should in general not be treated as 'initial reserves', because they can often be over-stated; for example where companies (and sometimes exploration teams within companies) seek finance in competition with other discoveries or projects.

- In assessing cumulative production to-date in order to calculate reserves, in some countries it is necessary to add in war loss; Kuwait for example lost about 2 Gb of its reserves when its wells were fired in the first Gulf War.

- And the caveats mentioned earlier over some of the data need to be considered; in particular on the reserves for FSU countries (where Laherrère suggests these should be corrected to 2P values by multiplying by ~0.7); and those for some Middle East countries (where here Laherrère subtracts 300 Gb in total from the commercial database URR data).

7.4 Comparison of 1P oil reserves with 2P

Now we quantitatively compare 1P oil reserves data with 2P. We first use data from Rystad Energy to look at the current situation on global reserves (and including some data on oil yet-to-find), and then give some recent data from China. Finally we present global data that examine the important issue of how these two classes of reserves have changed over time.

7.4.1 The current situation: Rystad Energy data on reserves

Rystad Energy have recently released data on their view of global reserves, Figure 37 and Table 1. Usefully they present their view of what proved reserves 'should' be (presumably under SEC rules or equivalent); of the 'most likely' (~2P) reserves in fields already in production ('existing fields); of the most-likely reserves of these fields plus those discovered but not yet in production, ('existing fields and discoveries') - which is the normal definition of reserves; and the case where oil in as-yet-undiscovered fields is also included. They then compare these estimates with the public-domain 1P data of the BP *Stats. Review*.

The above data are illuminating, and Table 1 bears close examination. The main conclusions are:

- Rystad's evaluation of global 'correct' 1P oil reserves is some ~400 Gb, i.e., *very much less* than as shown in the public-domain 1P data, which are in the range ~1500 Gb to ~1700 Gb, Figure 36.

- The company's estimate of current global 2P reserves (here of all

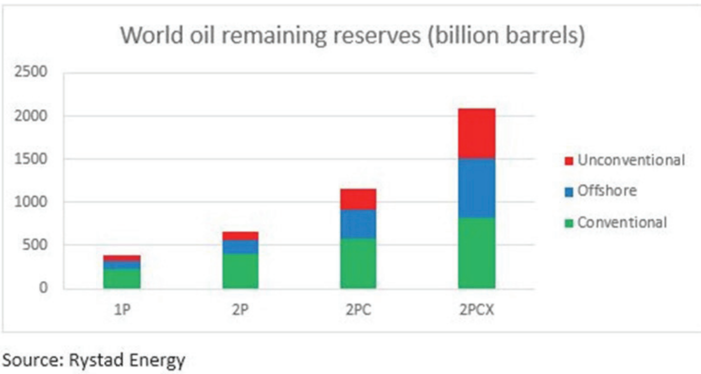

Figure 37. Rystad Energy Estimates as of 2016 of Reserves (1P to 2P); and the Expected all-oil volume recoverable if future discoveries and projects are included.

For source & notes see Table 1.

	1P	2P	2PC	2PCX	mmbbld*	2PCX life	BP SR**	BPSR vs. 1P	BPSR vs. 2PC
United States	29	40	109	264	9,4	77	55	193 %	50%
Russia	51	77	106	256	10,7	66	102	201 %	96%
Canada	24	41	106	167	3,8	120	172	703 %	163%
Brazil	10	17	41	120	2,4	136	13	133 %	32%
Mexico	6	8	16	72	2,3	84	11	172 %	67%
China	16	32	42	59	4,3	37	18	116 %	44%
Kazakhstan	5	11	28	45	1,7	73	30	549 %	106%
Argentina	2	2	8	29	0,6	145	2	122 %	30%
Norway	4	7	14	27	1,6	46	8	182 %	55%
United Kingdom	2	4	8	14	0,9	41	3	126 %	37%
Other non-Opec	25	44	76	216	8,9	66	74	291 %	97%
Non-OPEC	**175**	**283**	**555**	**1 269**	46,8	74	**486**	**277 %**	**88%**
Saudi Arabia	70	120	168	212	10,6	55	267	381 %	159%
Iran	32	59	99	143	3,3	119	158	498 %	159%
Iraq	19	48	94	117	4,0	81	143	750 %	153%
Venezuela	12	22	41	95	2,4	110	301	2609 %	742%
Kuwait	23	41	48	52	2,7	53	102	446 %	211%
UAE	23	35	42	48	3,1	42	98	432 %	233%
Qatar	7	11	40	44	1,4	84	26	385 %	65%
Nigeria	6	10	22	30	2,1	40	37	584 %	170%
Other Opec	15	26	44	82	4,9	46	107	734 %	244%
OPEC	**205**	**372**	**597**	**823**	34,5	65	**1212**	**590 %**	**203%**
World Total	**381**	**655**	**1 152**	**2 092**	81,2	71	**1698**	**446 %**	**147%**

*	Global production excludes natural gas liquids, biofuel and refinery gains
**	Reserve estimate from national authorities, as reported in BP Statistical Review
1P	Proved reserves, conservative estimate in existing fields
2P	Proved+Probable, most likely estimate in existing fields
2PC	Most likely estimate for existing fields and discoveries
2PCX	Most likely estimate for existing fields, discoveries and yet undiscovered fields

Note: All reserve numbers are Crude+Condensate including non-commercial volumes

Table 1. Rystad Energy Estimates as of 2016 of Reserves (1P to 2P); and the Expected all-oil volume recoverable if future discoveries and projects are included.

Notes:

1. Terminology: Rystad Energy uses the term ‘fields’, but since the data apply to both conventional & non-conventional oil, this presumably covers both fields and projects. Rystad also uses ‘existing fields’, and here this presumably refers to fields in production or discontinued; fields already discovered but not yet in production they appear to term ‘discoveries’.
2. The Rystad press release accompanying these data reads: “‘*United States now holds more oil reserves than Saudi Arabia.*’

- Per Magnus Nysveen, Head of Analysis, Rystad Energy, July 04, 2016

A new independent estimate of world oil reserves has been released by Rystad Energy, showing that the US now holds more recoverable oil reserves than both Saudi Arabia and Russia. For US, more than 50% of remaining oil reserves is unconventional shale oil. Texas alone holds more than 60 billion barrels of shale oil according to this new data.

The new reserves data from Rystad Energy also distinguishes between reserves in existing fields, in new projects and potential reserves in recent discoveries and even in yet undiscovered fields. An established standard approach for estimating reserves is applied to all fields in all countries, so reserves can be compared apple to apple across the world, both for OPEC and non-OPEC countries. Other public sources of global oil reserves, like the BP Statistical Review, *are based on official reporting from national authorities, reporting reserves based on a diverse and opaque set of standards.*

Some OPEC countries like Venezuela report official reserves apparently including yet undiscovered oil, while others like China and Brazil officially report conservative estimates and only for existing fields.

Rystad Energy now estimates total global oil reserves at 2092 billion barrels, or 70 times the current production rate of about 30 billion barrels of crude oil per year. For comparison, cumulatively produced oil up to 2015 amounts to 1300 billion barrels. Unconventional oil recovery accounts for 30% of the global recoverable oil reserves while offshore accounts for 33% of the total. The seven major oil companies hold less than 10% of the total. This data confirms that there is a relatively limited amount of recoverable oil left on the planet. With the global car-park possibly doubling from 1 billion to 2 billion cars over the next 30 years, it becomes very clear that oil alone cannot satisfy the growing need for individual transport."

3. Laherrère questions some of these data in a very detailed article dated 3rd August 2016: *'World, US, Saudi Arabia, Russia & UK oil production & reserves - Comments on Rystad 2016 world reserves*. In this he writes on the estimates for US light-tight oil (LTO): *In contrary [to conventional oil fields] LTO fields are new (after 2008); … there are not enough historical data to check the methodology and in particular the recovery factor. No one can claim to be right in estimating LTO reserves (being the cumulative production when exhausted), because there are not yet any abandoned LTO fields.*

Source: http://www.rystadenergy.com/NewsEvents/PressReleases/united-states-now-holds-more-oil-reserves-than-saudi-arabia discovered fields and projects) is ~1150 Gb. This is commendably close to the 1200 Gb or so one might estimate from Figure 24 (for 2015); and notably is some ~500 Gb lower than the public-domain *1P only* estimates mentioned above.

- If both discovered and as-yet undiscovered fields (and projects) are included, Rystad estimates the recoverable volume of all-oil remaining as ~ 2100 Gb. If added to the cumulative production to 2015 of 1300 Gb, this gives the global all-oil URR as ~3400 Gb. If just conventional oil is considered (including offshore) the total remaining including undiscovered is 1500 Gb. If we assume cumulative production to-date of conventional oil is ~1200 Gb, the global URR for this oil becomes 2700 Gb. See discussion of URR estimates in Section 11.

7.4.2 Reserves data for China

Here we look at the annual discovery data for China, as indicated by discovered reserves; where Figure 38 shows data from two different sources. As the Figure shows, there are considerable differences between the IHS data and those from Chinese statistics, and hence where this provides yet another example where caution over data sources is required.

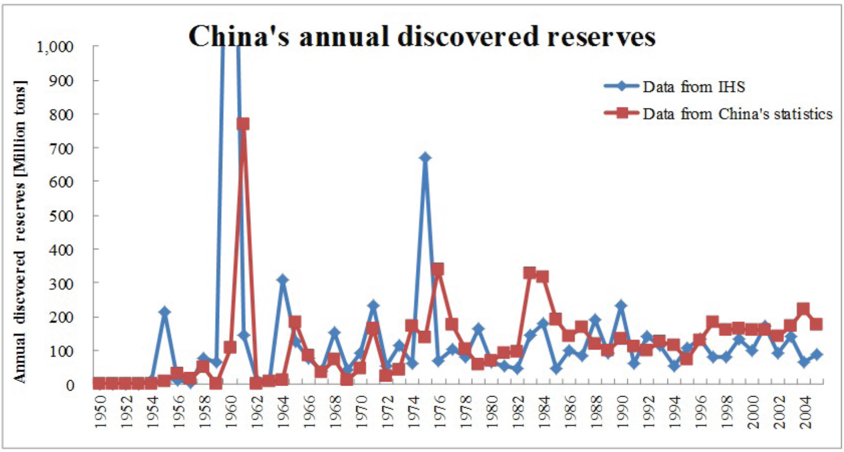

Figure 38. Oil Discovery data for China, 1950 – 2005.

Note: Here we can examine the data for China's largest conventional oil field, Daqing, discovered in 1959.This field is currently estimated to have had initial reserves of ~2.2 Gt (Wikipedia), which seems to confirm that the IHS Energy data are backdated 2P; while the Chinese statistics would seem to be possibly also 2P, but on a current-basis.

Sources: IHS Energy, Chinese official statistics.

7.4.3 Comparison of 1P vs. 2P reserves: Changes over time

Now we turn to the critical question of how 1P and 2P oil reserves have changed over time. As mentioned earlier, it has not just been the difference between these two classes of reserves that has fed the confusion on future oil production, but also – and more importantly – their change over time. This is shown in Figure 39, which shows the evolution of global 1P vs. 2P oil reserves, and indicates the main reasons for the discrepancies between these estimates.

As Figure 39 shows, for many years the total global volume of proved (1P) oil reserves as reported in the public domain was, as one would expect, considerably smaller than the global proved-plus-probable (2P) reserves as reported in industry databases. This situation changed steadily over time, with the explanation being a combination of the following:

- For most countries, the growth of their 1P estimates towards their 2P estimates as fields became more developed, and hence the probability estimate ranges narrowed. (Note that especially in the early years, and particularly for the US and Canadian data, the size of these omitted *probable* reserves were large.)

- The additional effect of this narrowed gap between the 1P and 2P estimates in reducing the underestimation error due to 1P aggregation.

- The reduction over time of the effect of 1P data being current at the date shown (i.e., estimates made at that date); vs the 2P data being backdated data, (i.e., in this plot reflecting 2014 knowledge of the size of remaining reserves in fields discovered as of the dates shown).

- The inclusion in the 1P data since the mid-1980s of the large, mainly spurious, OPEC ‘quota wars’ increases.

- The inclusion since about 2001 of increasingly large quantities of *non-conventional* oil reserves in the 1P data. Industry 2P data also include reserves estimates for the non-conventional oils, but only for specific extraction projects as they are announced, where - to-date at least - such volumes are considerably lower than the reserves of non-conventional oil included in the 1P data.

The main lessons from Figure 39 are:

- If 1P data are used, global reserves of ‘all-oil’ (including condensate and NGLs) have shown an apparent very encouraging ever-upward trend.

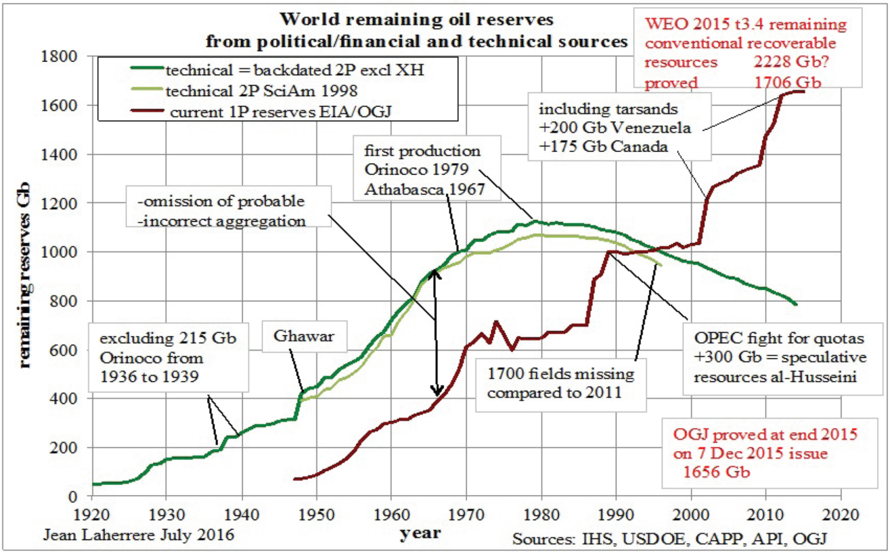

Figure 39. Global Oil Reserves. Difference between Current-basis proved ('1P') reserves as given by public-domain data and Backdated proved-plus-probable ('2P') reserves based on oil industry 'scout' 2P data, adjusted by Laherrère.

- Leftmost (dark green) line (exhibiting a peak in ~1980 at ~1,150 Gb): Laherrère's estimate of global 2P backdated oil reserves, 1920 to 2010, excluding NGPLs and extra-heavy oils (primarily tar sands and Orinoco oil). Data are from industry databases but adjusted by removing 300 Gb of almost certainly "political" reserves from Middle East reserves, and 30% of FSU reserves.

- Next leftmost (grey-green) line: The corresponding data as used in the 1995 Petroconsultants study that underpinned the Campbell and Laherrère 1998 Scientific American 'The End of Cheap Oil' article.

- Rightmost (magenta) line: Data from the US EIA and Oil and Gas Journal (OGJ) of public-domain current-basis global 1P oil reserves, 1947 to 2014, including extra-heavy oil.

Notes:

1. As explained the two curves are not strictly comparable, due to inclusion of different categories of oil.

2. Clearly visible in this plot are the OPEC 'quota-wars' increases in the 1P reserves; as are the majority of the increases in these reserves since the year 2000 due to the inclusion of tar sands and Orinoco reserves; and the smaller amount, since about 2010, from the inclusion of US 'light-tight' oil reserves.

Source: J. Laherrère; from sources listed on the chart.

- By contrast, if global backdated 2P global *conventional oil* reserves (i.e., after the very heavy oils & NGPLs have been taken out) are examined, these peaked in about 1980, and have been in steady decline since.

Figure 39 gives the explanation for the counter-intuitive result of current global public-domain *proved* (1P) all-oil reserves (at ~1500 - 1700 Gb) being some 500 Gb *greater* than the oil industry *proved-plus-probable* 2P all-oil reserves (at 1150 Gb according to Rystad, Figure 37; and ~1200 Gb according to IHS, Figure 24; respectively). This is due to a combination of the OPEC 1P reserves overstatements, with the fact - mentioned above - that the 1P reserves contain large volumes of assumed reserves for the non-conventional oils, primarily Canadian oil sands and Orinoco oil.

Note that if only *conventional oil only* is considered (but including NGLs), then the global estimates of the 1P and 2P reserves (if including NGLs) are closer, both roughly in the region of 1000 Gb or so. This approximate equality is essentially down to chance, with the conservatism of 1P estimates being roughly compensated for by the OPEC 1P overstatements.

Another way to look at this evolution of the 1P and 2P reserves data is in the corresponding global R/P ratios. These are shown in Figure 40.

As can be seen in Figure 40, the apparent 'ever-upward' trend of the 1P-data R/P ratios contrasts sharply with the high, and since 1940 declining, backdated-2P-data R/P ratio. Note that finding so much oil ahead of need is counter to standard economic thinking, and where the explanations for this are given in Chapter 5 of Bentley (2016a).

7.5 Oil Reserves Data: Summary and Discussion

To conclude this section on reserves data, first we summarise the key differences between how the 1P and 2P oil reserves data are generated; summarise some aspects of these data, and give an example of where this difference is still not understood.

7.5.1 Summary of 1P and 2P reserves

Published tables of proved (1P) oil reserves by region or country:

- are estimates made at the time;

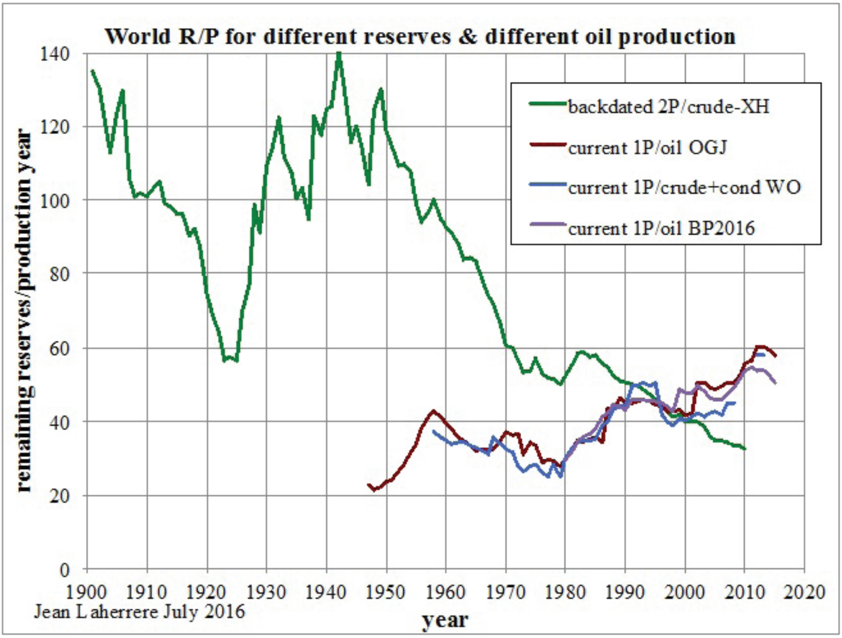

Figure 40. Comparison of 'Reserves to Production' (R/P) Ratios, for Current-basis 1P vs Backdated 2P Oil Reserves, since 1900.

(Note: In general R/P ratios *should have no place* in oil forecasting: On the positive side, they make no allowance for quantities of oil that may be discovered or otherwise become recoverable in future; but - and far more dangerously - on the negative side an R/P ratio often indicates significant quantities of oil remaining, but where the *production peak* of this oil is near, or already passed.)

Source: Laherrère, from sources listed, where 'backdated 2P' are industry 'scout' data.

- in the past, and still to some extent, have been conservative values where they refer to commercial oil company reserves, in the sense of following SEC reporting rules or equivalent;
- suffer from statistical under-reporting due to aggregation;
- in many cases are primarily *un-audited government statements*, such that:
  - they are again conservative if reported by certain governments (such as excluding discovered but as-yet-

unsanctioned fields);

- since the mid-1980s have included the significant OPEC 'quota wars' overstatements;
- remain unchanged for many countries, and sometimes for very long periods;
- and most recently, in some countries, especially Canada and Venezuela, include generous estimates (far exceeding 'proven') of non-conventional oils.

By contrast, the proved-plus-probable (2P) oil reserves in industry datasets:

- are generated from 'scout' data, and hence - notionally at least - are independent of government influence;
- are almost always backdated (i.e., reflect *to-day's* estimates of the recoverable oil that fields or projects originally contained, reduced by their cumulative production to-date);
- aim to give 'most-likely' estimates of field or project remaining reserves under reasonable assumptions on technology and oil price;
- are essentially correct under aggregation, being approximately mean-value data;
- for non-conventional oil reflect the recoverable oil in *announced* projects, and hence exclude consideration of potential future projects.

In other words: chalk and cheese. For considerably more detail of the definitions and severe problems of oil reserves data globally, and by different country, see Laherrère (2008 and 2016).

7.5.2 Discussion of 1P and 2P reserves data

For obvious reasons, public-domain 1P oil reserves data should *not* in general be used for oil forecasting. But if these are the only data to which you have access, then for forecasting production of conventional oil by country - to see, for example, when Nigeria, Russia or China will reach their peak in production - and also globally, the procedure set out in Bentley (2015a) can be used, where this draws on experience of oil forecasting using 2P data.

Note as mentioned above, some authors such as Laherrère and Campbell judge that the industry commercial 2P data warrant significant reduction in certain cases, for example the FSU data, and for certain Middle East countries; see also Annex 6.

Of course 1P and 2P data are not always so very different, depending on sources, and especially relatively late in a region's production; see for example of the difference (except for recent discoveries) between 1P and 2P data for the Gulf of Mexico given in Annex 6.

Moreover, in Laherrère's words: '*Past discoveries have to be compared using mean values and the 'present' method (to-day's estimates of volume and future oil price). The big problem is to distinguish current (i.e., original, at the time) reserves with to-day's backdated reserves. Oil reserves should be always given with a date and an assumed future oil price: conventional (easy and cheap) reserves do not vary much in volume with oil price, whereas reserves of non-conventional oil (EOR, the 'extra-heavies' & 'light-tight' oil) depend significantly on the future price of oil.*'

Finally in this section, we note that we have given so much attention to the '1P vs. 2P' issue because – surprisingly – it is still a source of confusion. This is well illustrated by a recent statement from BP's Group Chief Economist (Dale, 2015):

> "*But in practice, estimates of recoverable oil resources are increasing all the time, as new discoveries are made and technology and understanding improves. And, importantly, they are increasing far more quickly than existing reserves are consumed. In very rough terms, over the past 35 years, the world has consumed around 1 trillion barrels of oil. Over that same period, proved reserves of oil have increased by more than 1 trillion barrels.*
>
> *Put differently, for every barrel of oil consumed, another two have been added. Total proved reserves of oil – reserves of oil which, with reasonable certainty, can be economically recovered from known reservoirs – are almost two-and-a-half times greater today than in 1980.*"

As readers will now be aware, this statement - while strictly correct as far as public-domain proved reserves are concerned - is extraordinarily misleading, as shown in Figure 39. (Note that BP's *Stats. Review* is a valuable service the company provides to the global energy community; it is mainly with the oil reserves data, and use of R/P ratios, where analysts need to exercise considerable caution.)

8. Data on Reserves Growth – The Impact of Technology, and Price

Now we return to one of the important caveats raised above in connection with the 2P oil discovery data, and where this impacts the 2P reserves data also. This is that these data *do not include* allowance for future 'true 2P reserves growth'; i.e. for the expected future gains in field or project volumes (and hence also aggregated volumes) caused by advances in technology, or a higher oil price.

And to re-state: For the *1P reserves*, which - certainly in the past - were generally very conservative data, growth in these reserves was always to be expected, as these initial proved estimates grew over time towards the more-likely proved-plus-probable values. However, in this section we focus on 'real' reserves growth, i.e. growth over time in the 2P data; but where much of the discussion of reserves growth still conflates '1P growth' with 2P.

To start this section we first look at *conventional* oil, and note that *theoretically* the potential for 'real' reserves growth in such fields is large. Conventional oil fields show an extraordinary wide range of recovery factors (Figure 41), due a wide variety of physical and geological conditions within the reservoirs. But on volume average, the current global recovery rate in conventional oil fields is only some 40% or so (Figure 42), therefore *theoretically* at least there is considerable scope for increased yield.

But as mentioned earlier, the topic of the potential reserves growth in the future is complex, and a variety of considerations say the actual reserves growth likely to be seen is probably not so very great. Hubbert developed a model for reserves growth for *proved (1P) reserves* data in the US (where current US and Canadian non-frontier IHS Energy data are still only on a 1P basis); while Klett *et al.* (2005), and later Sorrell & Speirs (2014), looked at apparent reserves growth in the IHS Energy 2P data. But it turns out that much of this apparent 2P reserves growth can be ascribed to other causes, such as inclusion of additional fields, or changes in specific Middle East data, rather than to 'true 2P reserves growth'; see Section A4.3 in Bentley (2016a).

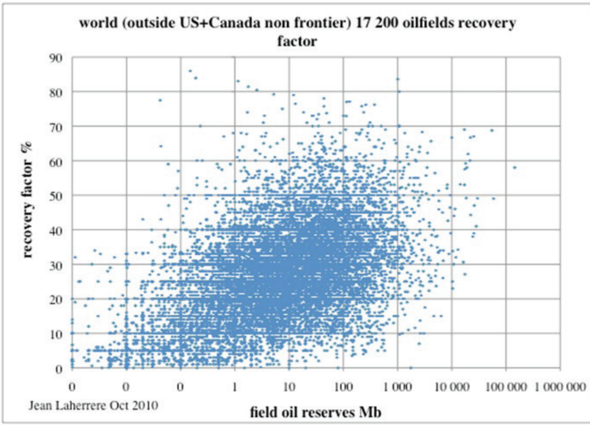

Figure 41. Scatter plot of Oil Field Recovery Factor vs. Size of Initial Reserves. World data excluding US and Canada non-frontier regions, comprising 17 200 fields.

Notes: - Log scale on reserves volume (so should read: 0.001, 0.01, 0.1, 1, 10, … Mb).

- Data give current values of field initial reserves divided by current value of assessed total volume of oil-in-place.

Source: J. Laherrère.

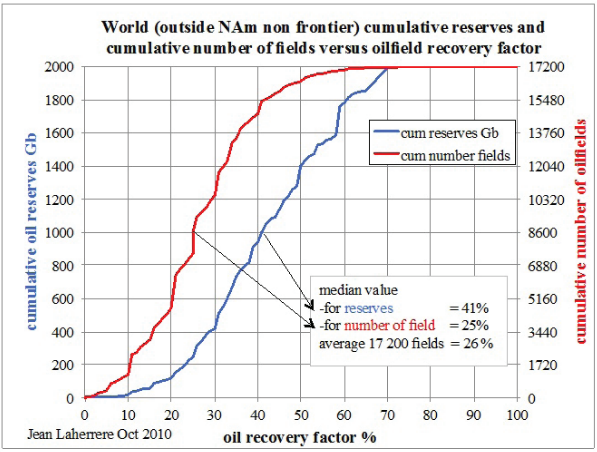

Figure 42. Oil Field Recovery Factor vs. Cumulative Initial Reserves; and vs. Cum. Number of Oil Fields. World data except for US and Canada non-frontier: 17 200 fields.

Source: J. Laherrère.

Though technology is advancing, and it is also true that a sustained high oil price will often allow a greater volume of oil to be retrieved from a given field, some judge that the likely total 'reserves growth' gain for *conventional* oil from technology and price combined, for regions and globally, will probably be between perhaps only 10% to 20% or so of the corresponding currently-assessed URR.

(Note that others take a more optimistic view. Aguilera and Radetzki, 2016, for example, look at the gains from technology as applied to light-tight oil, and suggest that if the same technology is applied to conventional oil fields large increases in recovery factor could result.)

For non-conventional oil the scope for technology or a higher price to raise the recovery factor is dependent on the type of oil considered. For oil-sands oil where extracted by mining and upgrading, the recovery factor is already very high, so the scope for increase is small. Where this oil is extracted by an *in situ* thermal process the scope for increase is greater. Light-tight oil in the US is said to have already seen significant increases in recovery factor from its initial rather low figures, and many think that a sustained high price of oil will raise recovery factors further.

For other - currently very low volume - oils, such as oil from kerogen, or GTLs and CTLs, the data are too sparse to comment usefully.

9. Data on Fallow fields

In this section we look at data on 'fallow' fields. Globally there are many fields that have been discovered some time ago but not so far been developed, termed 'fallow fields'.

In some places, such as the UK, the fact that they have not been developed despite reasonable tax regimes, access to good technology, and a high oil price means they are mostly small or especially difficult in some way. For the UK, IHS Energy reports 800 field discoveries, twice the 400 reported by DECC; giving ~400 fields currently undeveloped, of which most in Laherrère's view will "*likely never be developed*", where this is especially the case if nearby platforms are dismantled.

By contrast, in some of the Middle East countries some of the fallow fields are large discoveries which are still unconnected to any pipeline, and which await political decisions on development.

Miller's results presented at an ASPO meeting in Vienna (Miller, 2012) indicated that up to 170 Gb of global 2P reserves had not been developed by 2008. While clearly some of this was in appraisal, or awaiting sanction, Miller's tentative conclusion was that perhaps up to 140 Gb of the 2P reserves at that date were potentially doubtful, and which reflected: oil in the dataset which had not been developed for a very long time; oil which had been produced, but where this has not been recorded; or oil in fields now abandoned, possibly reflecting over-estimation of the original reserves.

All forecasters need to make judgements on when - and if at all - to bring on such fields. 'Capacity' forecasts, such as IHS CERA's, are perhaps more likely to assume such oil is available sooner, as does the 'bump' in Miller's forecasts (see Bentley et al., 2009), while some forecasters (including Miller himself) are more cautious on when they think such oil can or will be developed.

10. Data on Oil Drilling (Particularly of New-Field Wildcats)

Data on oil drilling *per se* is useful in near-term forecasts, but is generally not examined in detail when making longer-term forecasts; the general assumption being that drilling will be adequate to find and produce whatever oil may be out there once demand and price rise sufficiently.

But for some classes of long-term oil forecasting drilling information is required, that of true exploration wells, the 'new-field wildcats' (NFW's). This is because these data are key to correctly understanding, via so-called 'creaming curves', how much oil has been discovered in the past, and is likely to be discovered in future.

In this section we first discuss the data on rigs and then on wells, and finally the important NFW data required for discovery creaming curves.

10.1 Data on rigs

General data on oil drilling activity come from the public domain, and from the consultancies. Globalshift Ltd. gives charts of some of its drilling data free on its website, as does Baker Hughes. Figure 43 gives data on the number of drilling rigs operating globally and in the US since 1975.

Figure 44 breaks down the data on rigs operating in the US since 1949.

10.2 Data on wells

Now we turn to US data on numbers of wells drilled. Figure 45 shows how the number of oil wells drilled have varied with oil price since 1920, and Figure 46 gives the well numbers for both oil and gas over a nearly similar time period (and identifies dry wells, which some see as the exploration geologist's touchstone for reality in any data!).

Figures 47 and 48 give additional data on US wells.

10.3 'Creaming curves': Data on exploration wells

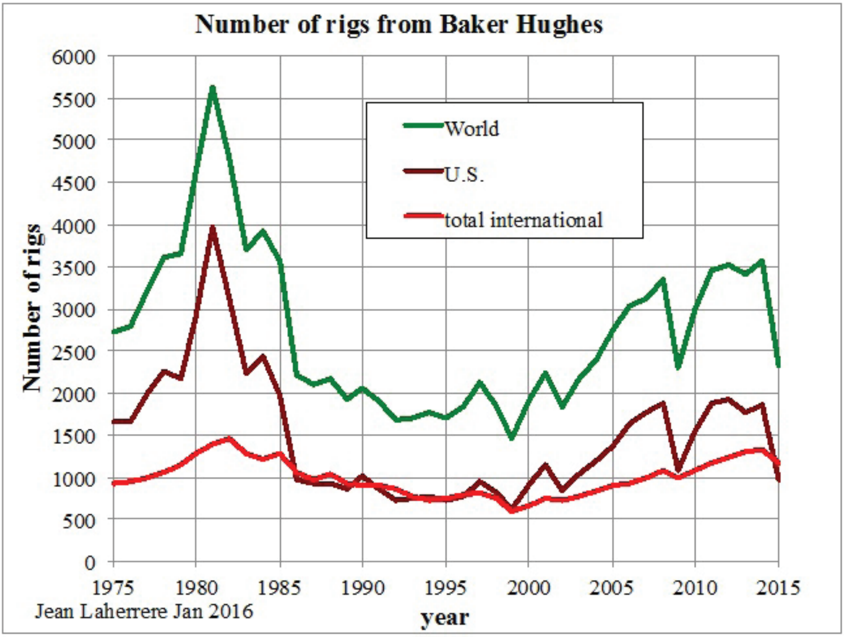

Figure 43. Number of Drilling Rigs Operating Globally, and in the US, since 1975.
Source: J. Laherrère; data from Baker Hughes.

As mentioned above, particularly useful for those forecasting oil production in the longer term are 'creaming curves'. These plot

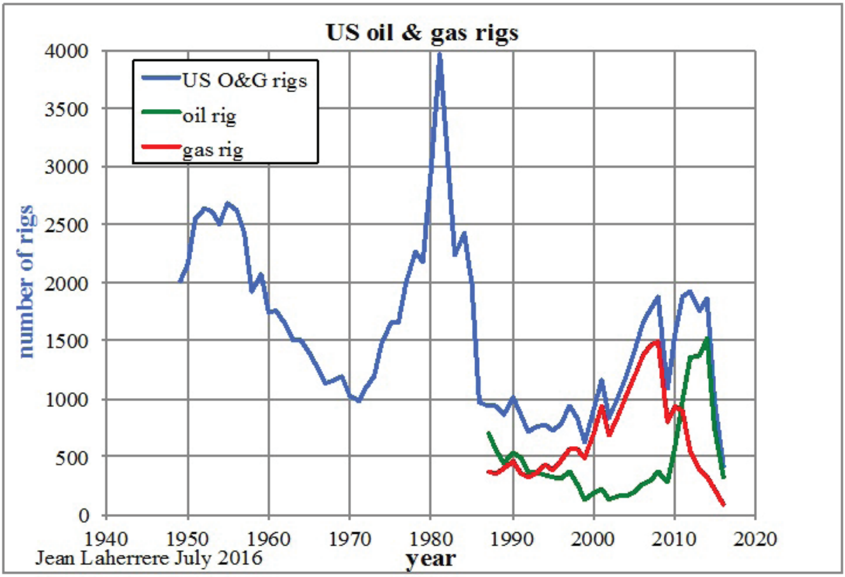

Figure 44. Number of Oil and Gas Drilling Rigs operating in the US, 1949 to 2015.Note: Laherrère writes: "*Most of the drilling is done in the US. The peak of rigs was 4500 in 1982, down to less than 1000 from 1986 (oil price counter-shock) to 2000, peaking again at 2000 in 2008 and 2011, with a sharp decline in 2014.*"
Source: J. Laherrère; data from EIA and Baker Hughes.

cumulative oil discovery on the ordinate against an abscissa, where the latter typically is date, number of fields discovered, or exploration wells (NFWs) drilled.

Each of these plots has advantages. A plot vs. date is the easiest to make, as all that is needed are the 2P discovery volumes in fields and the dates of corresponding discovery; examples are Figures 24 and 27 to 29 above. But exploration effort in a region can be impacted by a wide variety of factors, such as limitations on access, changes to commercial terms, war or civil unrest, introduction of a new safety regime, or changes in the oil price. So if one is looking to draw information from the *discovery trend*, the other two choices of abscissa are often more informative than date.

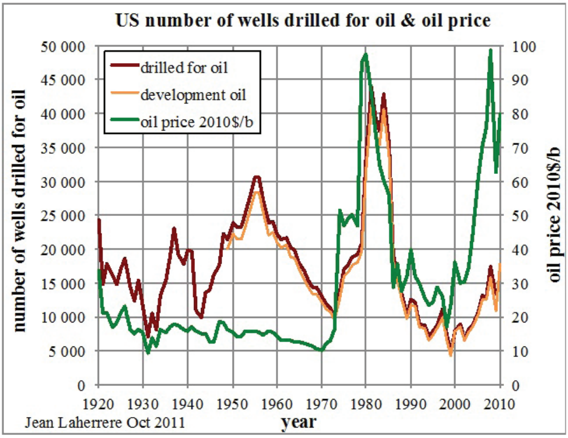

Figure 45. Number of US Wells drilled for Oil, vs. Oil Price, 1920 – 2010.
Source: J. Laherrère.

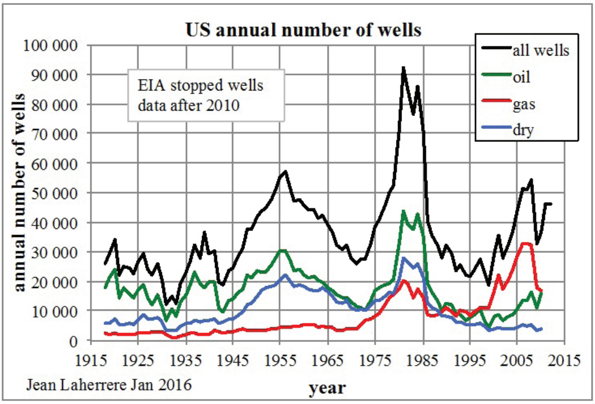

Figure 46. US Annual Number of Wells Drilled, split by those that found oil, gas or were dry.

Notes: - EIA stopped reporting number of wells after 2010.

- These are all wells; exploration plus development. 'True' exploration wells (NFWs) typically yield a much higher percentage of dry wells than indicated here; where the drilling 'success ratio' for development wells is typically 80% or so, while that for NFWs only perhaps typically 10%; but where the definition of 'exploratory well' depends upon country, in part because of tax rules.

- **Laherrère notes:** *"It is amazing to find that the number of wells drilled in the US since 1918 displays several almost-symmetrical cycles."*

Source: J. Laherrère.

Figure 49 shows a global creaming curve vs. *number of fields*

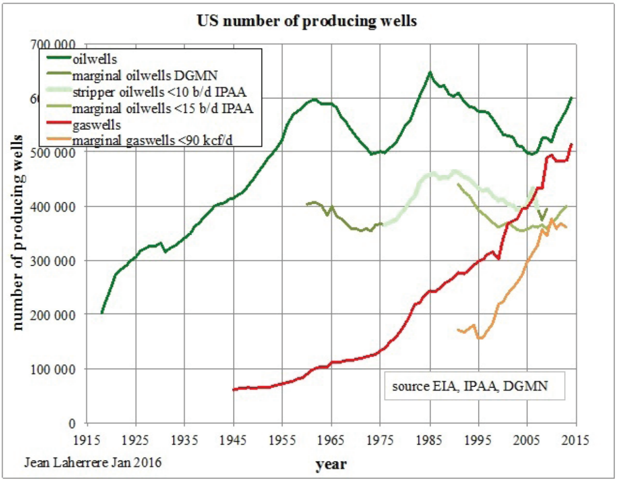

Figure 47. Number of US Producing Wells.

Laherrère notes: "*The number of producing oil wells since 1945 displays a peak in 1960 and 1985 (before the oil counter-shock). It is interesting to see the number of marginal wells (defined as producing less than 15 b/d or 90 kcf/d) or stripper wells (defined as producing less than 10 b/d or 60 kcf/d) (despite that DGMN marginal = stripper IPAA).*"

Source: J. Laherrère.

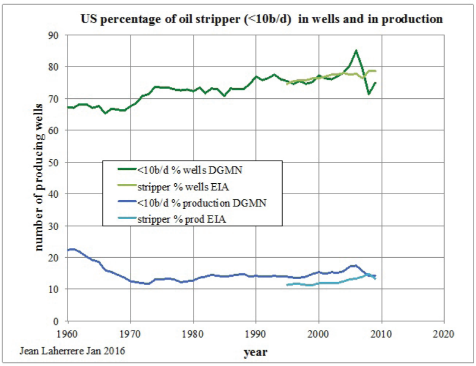

Figure 48. More detail on US Stripper Wells.

Laherrère notes: "*It is interesting that the US oil strippers (≤ 10 b/d) since 1970 represents about 75 % of the number of producing oil wells and about 15 % of US oil production. The EIA reports that the average production of the strippers was 3 b/d in 1976, and down to 2 b/d by 2007.*"

Source: J. Laherrère.

from Laherrère. This is for the world, but excludes US and Canada non-frontier regions (where, as explained earlier, for these regions the 2P discovery data are not generally available). Also shown are various discovery phases by date, as different levels of knowledge and technology came into play. In such a plot (i.e., discovery vs. fields) the 'extrapolated ultimates' are perhaps more easily judged than in the corresponding plot vs. date; e.g., Figures 24 etc.

In theory, probably the most useful creaming curves are those where the abscissa is the number of 'true' exploration wells (new-field wildcats). For example, in the major 1995 oil consultancy study for Petroconsultants, Laherrère and Campbell plotted up the discovery creaming curves vs. NFWs for nearly all regions being examined (Petroconsultants, 1995). However, given the problematical nature of some of these data (see for example the case of China, given below) Laherrère now reports: '*World NFW data are now sufficiently*

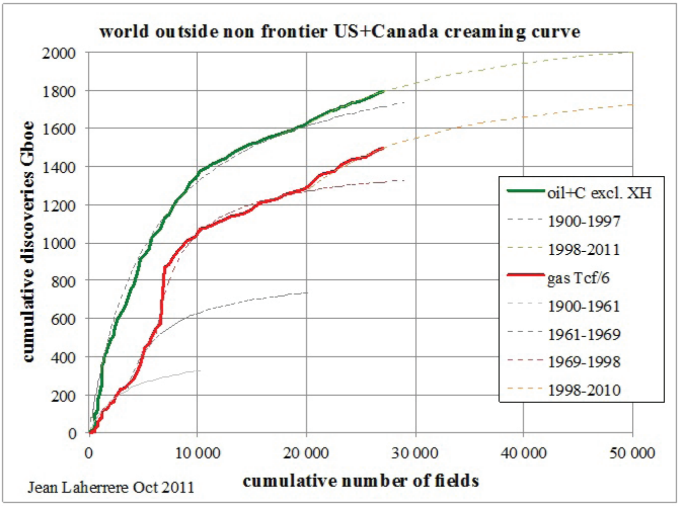

Figure 49. Global Oil and Gas Cumulative 2P Discovery data vs. Number of Fields Discovered (i.e., 'Creaming curve vs. fields'); excluding US and Canada Non-Frontier regions.

Notes: Oil discovery is for crude oi less extra heavies; and excludes NGLs

Laherrère notes: " *Using backdated 2P discoveries the creaming curve for the world outside US & Canada non frontier is extrapolated towards 2000 Gb.*"

Source: J. Laherrère.

unreliable that currently for global creaming curves I no longer use these data, but instead the number of fields discovered.'

In terms of access to the data exploration wells, for the US such data are available from a variety of sources including the EIA, API and DGMN; and where Figure 50 plots the number of exploration wells in the US by category since 1945.

Global data on NFWs are usually only available from the main commercial data providers such as IHS Energy, and, as mentioned above, even here - not surprisingly, given the difficulty in accessing such data - these are sometimes problematical. Figure 51 shows the case of revisions over time in the IHS Energy dataset of NFW data for China. (Note that data on the number of wells drilled in China can be found in CNPC internal reports.)

11. Data on the Ultimately Recoverable Resource (URR) of a Field, Project or Region

Finally, in Part-1 of this paper on oil data, we examine the data on estimates of the ultimately recoverable resource (URR) of fields, projects and regions, and hence also globally.

For a field, the URR is usually estimated soon after the field is discovered, and where this estimate often changes (usually upwards,

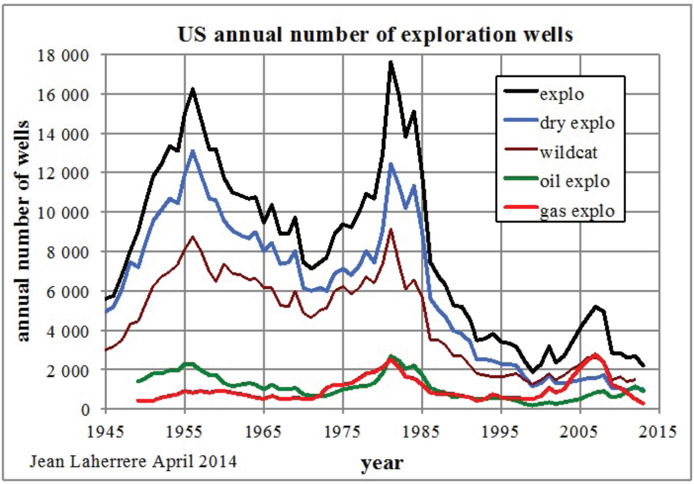

Figure 50. Annual Number of Exploration Wells Drilled in the US, 1945 – 2013. Source: J. Laherrère.

but frequently also downwards) through the life of a field. Numerically, a field's URR is its cumulative production to-date plus its remaining 2P reserves (where the latter may or may not include allowance for reserves growth). For the URR of a *region*, the latter's yet-to-find (or, equivalently, projects yet-to-propose for non-conventional oil) must be added in.

Arguably, of all the data required for oil forecasting, the URR data

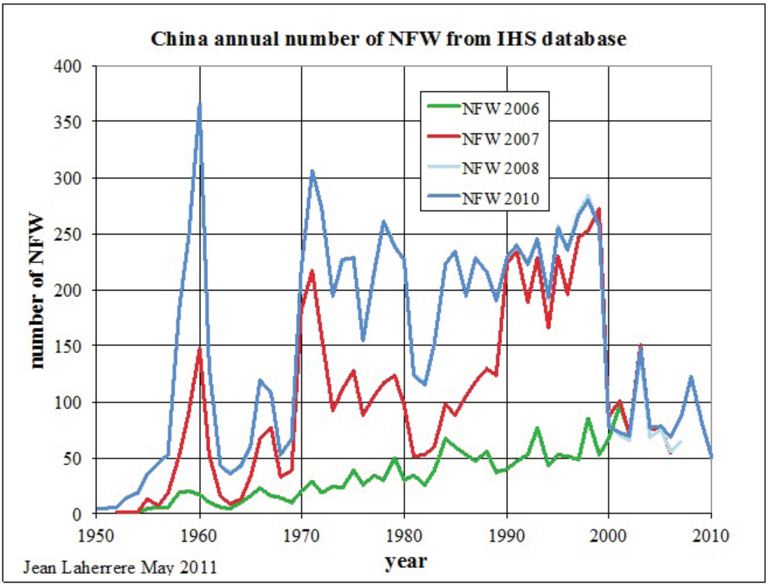

Figure 51. Variation in the data, from 2006 to 2010, of the Number of New-field wildcats drilled in China, 1950 – 2010.
Laherrère notes: "The IHS employee, Chinese-born US citizen Xue Feng, corrected sharply (multiplying by 5 the 1996 data) NFW data before 1999, but before finishing his work in 2007 he was jailed 8 years for spying: he was released in 2015; see http://www.theguardian.com/world/2015/apr/04/us-geologist-xue-feng-released-from-prison-in-china. Both Xue and IHS Energy had said in the past that they believed the database to be a commercially-available product. It was only classified as a state secret after Xue had bought it, according to Dui Hua. Thus now the NFW data are classed as a state secret in China, as similarly were the oil (but, curiously, not the gas) reserves in Russia until September 2013."
Source: J. Laherrère; original data from IHS Energy; and see also: https://en.wikipedia.org/wiki/Xue_Feng

are the most important. This is because, although there are a number of ways to forecast oil production that do not use URR estimates (see Annex 7), and also many of the 'bottom-up by-field' forecasters do not use URR data as such, in fact URR data provide an *overall check* on the reasonableness of any forecast: if the URR estimates used or implied in the forecast are unrealistic, then so almost certainly is the forecast.

11.1 Meaning of URR; and change in URR over time

Before we discuss URR data in detail, we must get two notions clear. Firstly, while the concept of a URR for a field or project is fairly straightforward (being the total quantity of oil extracted by the time production ceases), for a region, and more especially globally, the concept is far less clear. This is because it is likely that in some regions at least, oil production may never cease as small amounts continue to be produced for very long periods for high-value and specialty purposes. So for the URR for *regions*, we take the definition adopted by most modellers, as being the quantity of oil that will have been produced by some suitably distant date, such as 2070 or 2100.

The second notion that needs to be addressed is that many academics, and also general oil analysts, are still far from convinced that the concept of a URR – certainly as applied globally – has any validity at all; and follow the Adelman notion that total amounts of oil to be extracted are 'unknown and unknowable'. Responses to this view are given in Chapter 5 of Bentley (2016a), but it is sufficient here to point out the still under-appreciated fact that the more conservative (some would say, more realistic) estimates of global URR for conventional oil have changed *remarkably little* over the last half-century or so, despite very large gains in knowledge of how oils are generated, and hence likely to be found, and in techniques used to extract them.

For example, as early as 1949, M. K. Hubbert gave estimates for the global URR of *conventional* oil (ex NGLs) to be about 2000 Gb; for that of Canadian ('Athabaska') oil sands to be about 200 Gb, and of oil from kerogen in oil shales to be about 1000 Gb. The figure for conventional oil was based on an estimate by L. G. Weeks, which Hubbert doubled to allow for offshore oil. This estimate was something of a lucky shot at that date, as in 1956 Hubbert lowered the global conventional oil

URR estimate to 1250 Gb; and now had some 225 Gb (my estimate) as the URR for NGLs; 400 - 800 Gb for the oil sands URR, and 1300 - 3000 Gb for kerogen oil URR (Bentley, 2016b).

Significantly, however, by around twenty years later, from the early 1970s and with the large Middle East finds now properly evaluated, the estimates for the URR of global *conventional* oil, from a wide range of analysts including Hubbert, had coalesced into a range from 1800 to 2500 Gb (ex-NGLs); and where for many analysts this range *is still valid*.

For example, as we have seen above, interpretation of Figure 24 suggests an IHS Energy URR for global *conventional oil* of ~2500 Gb; Figure 27 gives Laherrère's URR estimate for crude oil less extra-heavies (and ex-NGLs) as 2200 Gb; Figure 28 gives Campbell's global URR for 'Regular Conventional' oil as 2000 Gb; while the Rystad Energy data (Figure 37), again for conventional oil, gives the global URR as ~2700 Gb. These data, and two other recent estimates (Miller, and Globalshift Ltd.), are summarised in Table 2.

The URR estimates in Table 2 should be contrasted with those of the IEA as given in Figure 53 and Table 3, and with the USGS estimates in Table 4.

11.2 Sources of URR data

As mentioned previously in Section 6 on oil discovery data, the sources of URR data for fields and projects are from operators or government agencies. For regions, as with the discovery data, most such data are only from the commercial database companies, or publications such as Campbell's *Atlas*, where the latter uses a variety of public domain and commercial sources, and where the URR data are adjusted based on the writer's judgement.

Figure 52 shows a range of historical estimates of global oil URR made up to 2005, taken from the US National Petroleum Council's 2007 "*Hard Truths about Energy*" report. These data display a large range, partly explained by including different categories of oil, but as can be seen in general this range of estimates has now somewhat stabilised. (For a detailed discussion of URR estimates, with a focus on looking at the difference in these estimates for *conventional* oil to explain differences in current global all-liquids forecasts, see Bentley, 2015b, and c; and Bentley, 2016b).

	Source	Conv. Oil URR (Gb)	NGLS (Gb)
Campbell	Fig 28	2000	~220 [N.B. For 'Regular conventional']
Laherrère	Fig 27	2200	300
Miller	ref	~2400	~300
Globalshift Ltd	ref	2500	370
IHS Energy	Fig 24	2500	n/a
Rystad Energy	Fig 37	2700	n/a

Table 2. Various Estimates of the Global URR for *Conventional* Oil (i.e., excluding extra-heavy oils, and also NGLs).

Notes: - Where shown, the URR for NGLs is *in addition* to the URR for conventional oil.

- Campbell's URR estimate is for '*Regular Conventional*' oil only (see Annex 2).

- 'ref'.: See data sources quoted in Bentley (2016b).

- On his global URR estimates, Laherrère writes: "*My ultimate for crude oil less extra-heavy has changed with time: I started with 2200 Gb (Copenhagen 2003) using the data from IHS but I found that the estimates of field reserves was too optimistic, mainly in OPEC countries and I reduced the ultimate to 2000 Gb (Bucharest 2005, ASPO 5; Italy 2005, ASPO 7; Barcelona 2008). But with discoveries in deepwater, in particular in subsalt, I increased the ultimate to 2100 Gb (Evora 2010); and with LTO to 2200 Gb (Sophia 2011), staying at this level up to now. My ultimate for all liquids was 3000 Gb (only one significant digit!) since 2002 (Sorbonne), staying at this level despite the change in conventional.*"

11.3 IEA Data on Global Oil and Liquids URRs

The IEA '*Resources to Reserves*' reports give a very useful chart of estimated size of global oil and liquids recoverable resources, vs. range of production cost. The 2013 data are shown in Figure 53.

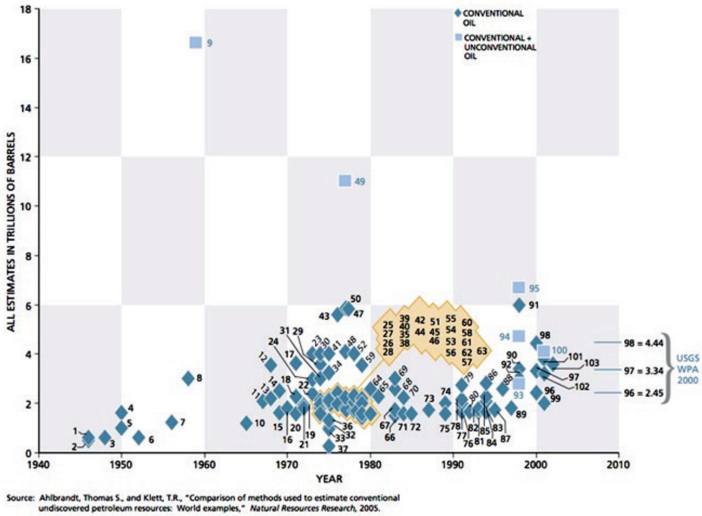

Figure 52. Global Oil URR Estimates since 1945.
Source: US NPC's 2007 "*Hard Truths about Energy*" report.

As Figure 53 shows, at this date the IEA estimated the *remaining* technically recoverable volumes of oil available to be:

- Conventional oil (assumed here to comprise MENA, Other conv., CO_2-EOR and Non-CO_2 EOR, Arctic, LTO and Ultra-deepwater): ~3350 Gb.

- Non-conventional oil and other liquids (assumed here to here to comprise extra-heavy oil and bitumen; and kerogen oil and GTLs and CTLs): ~3600 Gb.

If we then ascribe 1100 Gb of the ~1220 Gb 'already produced' by end-2012 to conventional oil, and 120 Gb to non-conventional oil, we arrive at the URR figures (rounded) of:

- Conventional oil: ~4500 Gb (includes EOR, LTO; and NGLs, assumed.)

- Non-conventional oil & liquids: ~3700 Gb (includes XH, kerogen , GTLs & CTLs)

- All-liquids (ex-biofuels): ~8200 Gb

Somewhat more recent data are given in Table 3.

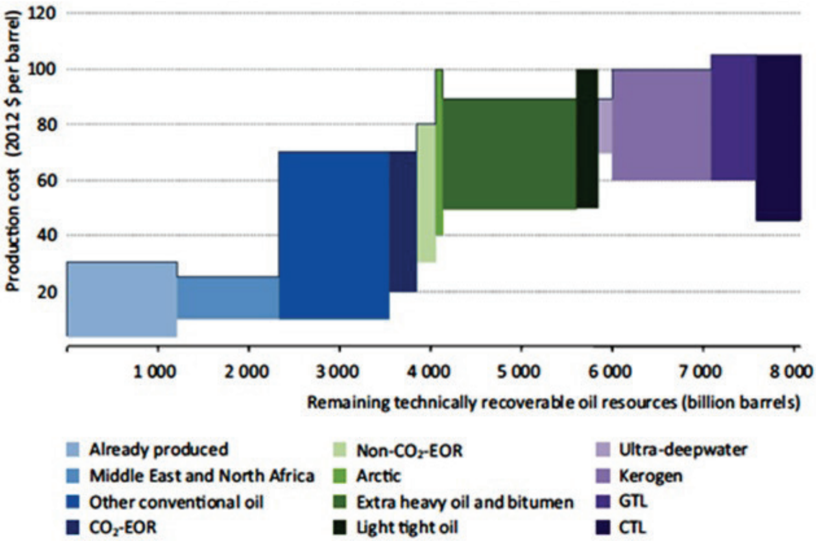

Figure 53. Estimated global remaining technically recoverable volumes of oil available, by category (in Gb), vs. Production cost range (in $2012/bbl).

Notes:

- EOR: Enhanced oil recovery; MENA: Middle East and North Africa; GTL: Gas to liquids; CTL: Coal to liquids.
- Volumes of oil potentially available are shown by length along the x-axis, not by the area indicated.
- NGLs are probably included in the data shown.

Source: IEA *Resources into Reserves,* 2013.

From Table 3, if we aim to put the data on the same basis as used for Figure 53, and assume:

- cumulative production to end-2014 to be ~1150 Gb of conventional oil (including NGLs) and ~130 Gb of non-conventional;
- move 'tight oil' into 'conventional';
- and add 500 Gb each for the URRs of GTLs & CTLs (as in Figure 53);

we find that the IEA is here estimating URRs (rounded) of:

- Conventional oil:	~4300 Gb (includes NGLs and tight oil)
- Non-conventional oil & liquids:	~4000 Gb (includes XH, kerogen and GTLs & CTLs)

- All-liquids (ex-biofuels): ~8300 Gb

This is a similar result to Figure 53.

11.4 Problems with URR data

There are a number of problems with URR data, of which perhaps the main ones are:

	Conventional resources		Unconventional resources			Total	
	Crude oil	NGLs	EHOB	Kerogen oil	Tight oil	Resources	Proven reserves
OECD	320	150	809	1 016	118	2 414	250
Americas	250	107	806	1 000	83	2 246	233
Europe	60	25	3	4	17	110	12
Asia Oceania	10	18	-	12	18	58	4
Non-OECD	1 908	409	1 068	57	230	3 672	1 456
E. Europe/Eurasia	265	65	552	20	78	980	146
Asia	127	51	3	4	56	242	45
Middle East	951	155	14	30	0	1 150	811
Africa	320	87	2	-	38	447	130
Latin America	244	50	497	3	57	852	325
World	2 228	559	1 878	1 073	347	6 085	1 706

Notes: Proven reserves (which are typically not broken down between conventional/unconventional) are usually defined as discovered volumes having at least 90% probability that they can be extracted profitably. EHOB is extra-heavy oil and bitumen. The IEA databases include NGLs from unconventional reservoirs (i.e. associated with shale gas) outside the United States, assuming similar gas wetness to that seen in the United States, because of the lack of comprehensive assessment; these unconventional NGLs resources are included in conventional NGLs for simplicity.

Table 3. Remaining Technically Recoverable Oil Resources by Type and Region. Source: Table 3.4 from IEA *World Energy Outlook,* 2015.

(i). The judgment (as discussed earlier) by some analysts that current URR data as held in some commercial databases needs to be adjusted for a variety of reasons, where generally this means reducing the URR estimates.

(ii). URR estimates from the USGS, which from the year-2000 survey and subsequently are judged as unrealistically high by some analysts, due to over-allowance for reserves growth.

11.4.1 Downward Adjustment

The first aspect has been discussed above in terms of the oil discovery data reported by Laherrère and Campbell.

Laherrère, as mentioned, reduces commercial industry 'scout' oil discovery data as follows: by 300 Gb to allow for probable OPEC overstatement of *2P reserves*; by 100 Gb to allow for FSU reserves being approximately 3P rather than 2P; and by 200 Gb to allow for early extra-heavy Orinoco oil (i.e., non-conventional oil) being included in the industry scout 'all-oil' totals. Details of the rationale behind these various judgements are given in Annex 6.

Campbell, likewise, reduces the data on announced *1P reserves* to compensate for the long periods when these reserves have shown no change; and for certain OPEC countries where he judges that the 1P reserves data in fact probably reflect the *initial reserves* data for conventional oil in discovered fields.

11.4.2 USGS estimates of undiscovered oil

Finally, an important special case to discuss are the USGS estimates of undiscovered volumes (and see also Annex 6).

In the recent past, many of the 'mainstream' forecasters (such as the IEA, EIA, OPEC, some of the oil majors, and some consultancies) have based their oil forecast models on global URR estimates derived by the United States Geological Survey (USGS). These estimates since the year 2000 have included quite large amounts of oil allocated to reserves growth, and where some analysts at least have seen these URR estimates as being on the high side, at least in comparison with the 2P discovery data to-date. This is discussed in Bentley (2015b and 2015c, and 2016b). The relevant data are in Table 4:

Survey date	Reserves growth (Gb)	URR Conv oil (Gb)	NGLs (Gb)	URR Conv. oil (incl. RG & NGLs (Gb)
1991	n/a	~2300		
1994	n/a	2400		
2000	700	3000	~350	3345
2012	720	~3400	~400	~3850

Table 4. USGS Mean Estimates for Global URR of Conventional oil (including allowance for Reserves Growth from year-2000), and for NGLs; by date of survey.

Notes: RG = Reserves growth.

The USGS estimates in 2012 are only for *undiscovered conventional oil;* so total URRs (as shown here) have been estimated by adding in global conventional oil cumulative production to 2011.

Source: USGS, various publications.

11.5 Comparison of URR estimates for global conventional oil (ex-NGLs)

We are now in a position to compare the estimated URR values for conventional oil (ex-NGLs) that have been presented in this paper.

Table 2 gave the URR range from a variety of authors as ~2200 – 2700 Gb.

Table 4 indicates that the current USGS estimate for this global URR as ~3400 Gb; i.e., about 1000 Gb larger than the estimates in Table 2.

Table 3 suggests the current IEA URR estimate for global conventional oil (including LTO, but excluding NGLs; and assuming cumulative production to end-2014 of this class of oil is ~1100 Gb), to be ~3670 Gb; i.e., nearly 300 Gb higher than the USGS estimate.

Oil forecasters, and those who use these forecasts, need to be aware of these significant differences in URR estimates.

12. Concluding Remarks

We conclude this paper with three remarks of a more general nature. These cover the underlying problem of poor data for oil forecasting; the increased need for, and difficulty of, modelling demand-side issues; and the undoubted need for this paper to be improved.

1. Poor data

As this paper has shown, one of the major problems with oil forecasting has been the poor data available.

Campbell has written in effect that if the global oil data were of reasonable quality, the problems of forecasting oil production would be minimal, and much of the controversy over peak oil would disappear. This possibly overstates the case, as some analysts might still not be aware of the 'mid-point' peak in production, as this applies to conventional oil, so still be misled by the often-quoted apparent security of oil supply offered by the current relatively large global R/P ratio. Even so, if the poor data that led to the widespread misapprehension over 'reserves replacement' had instead been good data, then almost certainly a much better understanding of the world's oil future would have been likely.

In terms of the reserves data, Laherrère noted: '*In 1996 a reserves expert, E.C. Capen, stated: "An industry that prides itself on its use of science, technology and frontier risk assessment finds itself in the 1990s with a reserve definition more reminiscent of the 1890s."*' As explained elsewhere in this paper, since this statement was made a number of organisations and industry bodies have been working hard to improve this situation, but unfortunately much of the legacy of the past poor reserves data - and hence the incorrect conclusions drawn from them – still remains.

2. The increased need for demand-side modelling

A second area that needs commenting on is that most of this paper has been written from a 'supply-side' perspective. In the past a number of high-profile organisations carried out oil forecasting by undertaking detailed analysis of likely oil *demand* trends, and assumed - since there was still a lot of oil (in total) remaining - that supply would be more than adequate to meet this demand (see Annex 8 on past forecasts). Though this overall view was wrong in missing the crucial concept of 'peak at mid-point', the demand modelling itself was generally well done, splitting out demand by sector, and examining the likely trends in the underlying drivers of demand.

Today as have we have shown, the global supply of conventional oil has been getting increasingly difficult, such that global demand needs increasingly to be met from the intrinsically more-expensive, low-EROI non-conventional oils. If this were the only factor at play one could predict oil's future (on-average) price from essentially the marginal cost of the next non-conventional oil to be required, with demand then being set by some empirically-determined elasticity vs. price.

On top of this one needs to consider the fact that a number of forecast models predict that the rate that the non-conventional oils and 'other liquids' can come on-stream will *not* be sufficient to offset the decline in conventional oil production, so that global total all-liquids supply will decline. If this occurs, then the future price of oil is not set simply by the marginal cost of the various liquids, but also by the need for the oil price to rise high enough for 'demand destruction' to bring demand into line with this dwindling supply.

Moreover, this picture is muddied further by the question of 'peak demand', which a number of organisations predict will arrive earlier than 'peak supply'. One has to be a bit careful here, as 'peak demand' means two quite different things. It can mean a peak in demand caused simply by a high oil price; or, more significantly, a peak in demand caused by demand-reducing factors *other than price*, such as a desire to avoid reliance on politically risky sources of oil; or from constraints on demand (such as taxes or government fiat) aimed at mitigating climate change risks.

The need to impose such 'climate-change' constraints is looking increasingly likely. Recent research has indicated that the 1.5 °C limit above pre-industrial temperatures may already be built-in, with heat put recently into the oceans due to return to the atmosphere. And even the 2 °C limit looks very difficult; with CO_2 emissions from all fossil fuels combined needing to be reduced from about now (say, 2020) if any realistic and socially-bearable emissions-reduction pathway to reach this goal is to be met.

The upshot of the above considerations is that demand forecasting now needs to include both the supply-side constraints indicated in this paper, as well as the new (and probably difficult-to-model) 'peak demand' considerations. An important task, and not one for the faint-hearted.

3. The need for this paper to be improved

Finally in this paper, we point out the need for it to be considerably improved. In particular, the paper should essentially be regarded only as a draft, as we have not yet had the opportunity to seek feedback and corrections form the many data-supply organisations mentioned here. Without this feedback there is a near-certainty that many quite serious errors have been made. For this reason, following publication we will send this paper to those organisations that we think may usefully be able to comment, to solicit their views and corrections. If useful feedback is obtained, then it is the intention to publish a revised version of this paper in the Spring 2017 issue of this journal.

If in the meantime anyone has comments, contributions or criticisms to offer, these would be very welcome.

Notes:

- The authors are very grateful to two external reviewers who provided useful comments that have much improved this paper.

- A PDF version of this paper giving the Figures in colour is available from Noreen Dalton at: theoilage@gmail.com

Annex 1: Units and Acronyms

A1.1 Units

Often the unit for oil volume is the US barrel. (Laherrère notes: '*Because the oil barrel is not an official US unit, the EIA is obliged to add '42 US gallons' after barrel.*'). It is usually abbreviated as 'b' (though sometimes 'bbl', meaning 'barrels').

Conventionally in the literature this unit can take metric prefixes (e.g., kb: thousand barrels; Mb: million barrels; Gb: billion barrels); and for production rate per day takes the suffix '/d' (e.g., kb/d for kilo barrels/day, etc.). We recognise that the barrel is a non-SI unit, and Gb is even more of an offender; but these units are convenient and widely used.

Oil can also be measured by weight, often in metric tonnes, viz: kt, Mt, Gt; and kt/d, etc.; where a conventional density conversion is: 1 t = 7.33 b.

Gas is usually measured in volume at STP, e.g.: Tcf: Trillion cubic feet; where a conventional conversion factor in terms of energy content is: 1 Tcf of natural gas = 0.19 Gb of oil equivalent ('Gboe').

A1.2 Acronyms

1P: Refers to reserves, and to discovery data: Proved; proven. See Annex 2.

2P: Ditto: Proved-plus-probable. See Annex 2.

AAPG: American Association of Petroleum Geologists
AEO: EIA's *Annual Energy Outlook*
ASPO: Association for the Study of Peak Oil and Gas
BEPH: France's Bureau Exploration-Production des Hydrocarbures
BEIS: UK Ministry for Business, Energy & Industrial Strategy (formerly DECC)
BGR: Germany's Bundesanstalt für Geowissenschaften und Rohstoffe
BOEM: US Bureau of Ocean Energy Management
BP *Stats.*: BP *Statistical Review of World Energy*
BSEE: US Bureau of Safety and Environmental Enforcement
CAPP: Canadian Association of Petroleum Producers
CTLs: Coal to liquids. See Annex 2.
DECC: UK Dept. of Energy and Climate Change
DPR: US EIA monthly *Drilling Productivity Report*
EIA: US Energy Information Administration
EOR: Enhanced oil recovery. See Annex 2.
GTLs: Gas to liquids. See Annex 2.
IEA: International Energy Agency
IEF: International Energy Forum
IEO: EIA's *International Energy Outlook*
IFP: France's Institut français du pétrole
JODI: Joint Organisations Data Initiative

LTO: Light-tight oil. See Annex 2.
MMS: US Minerals Management Service
NGLs: Natural gas liquids. See Annex 2.
NGPLs: Natural gas plant liquids. See Annex 2.
NPD: Norwegian Petroleum Directorate
NRC: National Resources Canada
OGJ: *Oil and Gas Journal*
OPEC: Organization of the Petroleum Exporting Countries
PDVSA: Petróleos de Venezuela S.A.
SPE: Society of Petroleum Engineers
UKERC: UK Energy Research Council
URR: Ultimately recoverable resource. See Annex 2.
USGS: United States Geological Survey
WEO: The IEA's *World Energy Outlook*
WO: *World Oil* journal
XH: Extra-heavy oil. See Annex 2
XTL: Liquid fuels produced by conversion of non-oil sources. See Annex 2.

Annex 2: Definitions, including Categories of Oil

A2.1 Definitions

Terms concerning categories of oil are not fully settled. Here we use the following:

Conventional oil: Defined here as light and medium oil that has migrated from its source rock to a reservoir rock; usually having an oil-water contact; and where extraction is by primary recovery (own pressure, or mechanical pumping) or secondary recovery (natural gas or water drive). For reasons of the data already in some industry datasets, this definition can also include condensate, heavy oil produced by fairly standard thermal techniques such as 'huff and puff', and some oil currently (or expected soon to be) produced by enhanced oil recovery. Published data on conventional oil *production* often include natural gas liquids (NGLs), but in this paper the latter, where possible, are treated separately, as they come from gas wells having their own exploration history and production pattern.

However, it is accepted that even within such aggregate groupings there are problems of definition. One reviewer of this paper, for example, pointed out that hydraulic fracturing and other forms of stimulation (which 'change the surrounding material') are used in many oil fields; and that perforation after penetrating the casing also changes the surrounding material but is used in many conventional oil wells. In the reviewer's dataset conventional oil is classed as *'oil in fields'*.

A particular problem regarding the term 'conventional oil' is whether EOR oil, NGLs or 'light-tight' oil are included. Some authorities include one or more of these categories in conventional oil, others do not; and analysts need to be aware of these differences when examining published data.

Note 1: Campbell uses the term 'Regular Conventional' oil to exclude all very heavy oil (<17.5 deg. API), oil from >500 m water depth, Alaskan and other polar oil, and NGLs. The reason for these choices is that these excluded categories require different extraction and production profiles for modelling. Campbell notes that Canada has the cut-off for heavy oil at 25 °API and Venezuela at 22 °API, but that he adopts a lower cut-off for heavy oil at 17.5 °API so that "*all fields that can be produced in more or less normal ways may be included as 'Regular Conventional'.*"

Note 2: Laherrère points out that Canada has several cut-offs: CAPP <28°API; while the website http://www.centreforenergy.com/AboutEnergy/ONG/Oil uses <22,3°API. Figure A2.1 illustrates the classifications for light and heavy oil.

Note 3: For Laherrère, conventional oil is: '*Oil with a horizontal water-oil contact, or it is oil produced using primary and secondary recovery, which is improving only the pressure with water or gas injection; leaving tertiary recovery (steam, EOR, etc.) to non-conventional. Tertiary recovery is changing the physical or chemical factors of the fluids, and hence should be classed as non-conventional oil.*'

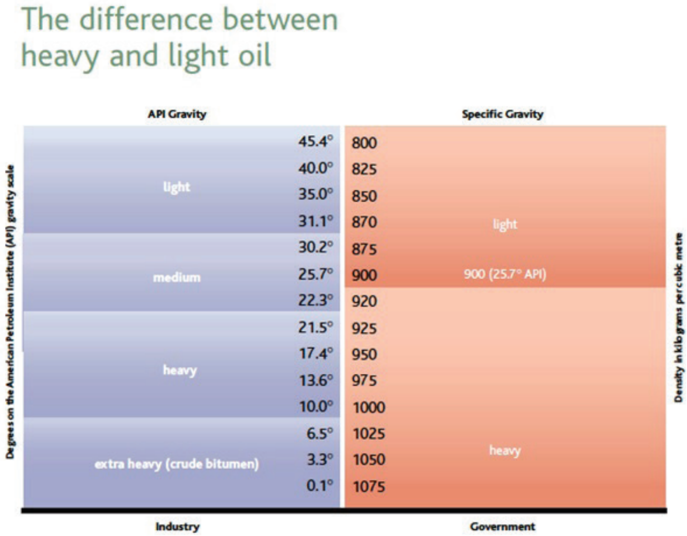

Figure A2.1 Classification of Oil by Degrees API, and by Specific Gravity.
Source: Canadian Centre for Energy Information, 2004.

Note 4: In general some of the gas from gas fields condenses at the surface, called 'condensate', and some liquids can be produced by processing, 'natural gas plant liquids' (NGPLs). Thus, as a simplification: NGLs = NGPLs + condensate; and where - very roughly - NGLs contribute ~12 Mb/d to global liquids production, and NGPLs perhaps ~9 Mb/d. But this is a confused topic, as the definition of, and inclusion within datasets, of these liquids are far from consistent, in part because some liquids can be identified and sold, and others are blended into oil. Laherrère notes that the IEA (following the NPD's approach) reports condensate either as crude oil or NGL, depending on how it is sold. The conclusion is that all 'gas liquids' data should be treated as approximate.

Enhanced oil recovery (EOR): Oil produced from an existing field by application of a tertiary recovery method such as N_2 or CO_2 injection, or use of other miscible liquids or chemicals. This oil is generally not seen as 'conventional' oil, as tertiary processes often - but by no means always - are used fairly late in a field's life (although this is now changing). EOR methods often incur significantly increased dollar and energy cost, and though they can be very effective in specific fields typically - at least to-date - yield relatively small extra volumes *in total* compared to the oil the fields would be expected to yield without their use, in the range of perhaps 5% to 15% extra oil.

The data on EOR in the US (Figure A2.2) show a fairly steady level of production from EOR projects since 1986, though where the number of such projects has declined since post second-oil-shock levels, and with a modest up-tick in number since the oil price rise of 2004.

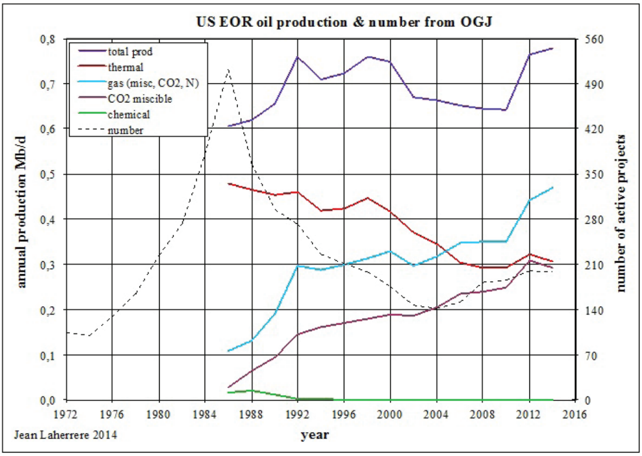

Figure A2.2. US data on volume of oil produced from EOR projects by type, 1986 - 2014; and also Number of projects, 1972 - 2014.
Source: Laherrère, data from *Oil & Gas Journal.*

Laherrère notes, however, that it is almost impossible to obtain *global* production data for EOR; and thus in his view '*it is best is to deal with the simple breakdown of crude oil less extra-heavy production, where global data can be obtained.'*

Extra-heavy oil: Refers to oil that is heavier than water (i.e., <10°API), and in the main, refers to tar sands (Athabasca), other bitumen, and Orinoco oil, but includes very viscous oil also. (Note that Athabasca and Orinoco oil have similar densities, but Athabasca oil being some 50°C colder is viscous ('bitumen') and needs steam treatment if produced *in situ*, whereas Orinoco oil can be extracted without such heating.)

Light-tight oil ('LTO', or 'shale-oil'): Oil extracted from rock that otherwise would be too impermeable for useful amounts of oil to flow to the (usually horizontal) borehole, by the use of high-pressure hydraulic fracturing combined with the use of 'proppants' that keep the fractures open despite the weight of overburden naturally trying to close these.

LTO has replaced in the US the term 'shale oil' to avoid confusion with 'oil shale' oil (oil retorted from kerogen), and because its production comes from tight reservoirs generally immediately proximate the source-rocks.

> Laherrère notes: "*'Light-tight' production (as shale gas), by starting around 2008 was claimed to come from 'new technology', including horizontal drilling and hydraulic fracturing; but in fact these techniques are over 50 years old. Shale gas production started in the US in 1821 at Fredonia (NY State) for lighting oil, in competition with whale oil which was then about \$(2015) 1000/b. When cheap oil arrived in 1859, the whales were safe, and shale gas production went down for a long time (despite the Big Sandy gas field being produced by fracking with nitro-glycerine in the 1960s; see Laherrère, Nice 2012). The Barnett shale gas was produced thanks to US DoE subsidies and a high price for gas (\$10/kcf in 2006). The Bakken LTO started in Montana and North Dakota when the oil price went above \$100/b*."

Oil from kerogen ('oil shale' oil): Oil produced from oil shale and similar rock types that contain significant amounts of the oil pre-cursor kerogen, and from which oil can be generated by retorting (pyrolysis) - either above ground or *in-situ*.

'All-oil': Conventional oil plus NGLs, EOR, extra heavy oil, light-tight oil and oil from kerogen,

'All-liquids': 'All-oil', plus refinery gain, gas-to-liquids, coal-to-liquids, and biofuels.

Reserves: That quantity of oil that has been discovered and is assessed as likely to be recovered under current or reasonably-expected technical and economic conditions. The reserves values usually (but not always) held in commercial industry databases are 'proved-plus-probable' ('2P') reserves, and reflect estimates based on expected decisions for field or project development using net present value (NPV) scenarios up to the end of production, see discussion in Section 7, and in Annex 5. By contrast, the public-domain *proved*

('1P') reserves data *do not* meet this definition; and proved reserves data in general are very misleading, see also Section 7 and Annex 5. Proved oil reserves are of no use for oil forecasting unless additional assumptions are made (Bentley, 2015a).

'Reserves' usually refers to the reserves *remaining* at a given date (and where this date should be reported with the reserves data); while 'original reserves' refer to the quantity in a field or region before extraction started. Often data on the latter have been updated to reflect *today's* knowledge, so may not match the value published when production started.

Reserves growth: Refers to the change (usually, but not always, an increase) in the estimated ultimate recovery (URR, see below) that occurs over time as fields or projects are developed and produced. See Section 8 above for discussion of this issue. (However, Laherrère notes: "*The reserves estimate should be the mean value which by definition should not change with time statistically, some increase should be compensated by some decrease. If the value changes it means that the estimation was badly carried out!*" – though he does allow that 2P reserves can change if the long term oil price changes.)

Resource: All of a specified hydrocarbon in-place, whether discovered or not, and whether technically or economically recoverable or not.

(Even this definition is not without ambiguity; as Miller asks: Does 'resource' include every molecule of the hydrocarbon in the rock, or just in sensible accumulations? The report *Undiscovered Petroleum Potential* by Laherrère, Perrodon and Demaison (Petroconsultants 1994) estimated that of all hydrocarbons generated, perhaps only 1% will be classed as reserves; the remaining 99% having been lost to the surface, or be unrecoverable in fields, or be still in the source rock, often trapped in fractures. For generated gas, some of this has been adsorbed into shale and coal.)

Here we define 'resource' as all of the hydrocarbon in a specified region; but use the term in a more restricted sense in 'resource-limited', as defined below.

Recoverable resource: That fraction of the resource that can be recovered under some stated or implicit level of technology and price. As mentioned earlier, for conventional oil (see the definition above) the global average quantity currently considered economically recoverable in existing fields is - very roughly - about 40% in volume terms of the in-place; while for conventional gas this ratio is - very roughly - about 80%.

Ultimately recoverable resource ('URR'); also called estimated ultimate reserves ('EUR'): This is quantity of oil judged likely to be extracted from a field, project or region by the end of production (and see also the definition of 'reserves', above). Note that the URR is usually not taken as referring to some 'true ultimate' figure, as this is hard to know. Firstly, though the URR is limited by the original oil-in-place, often the latter can only be estimated rather poorly, as it depends on extrapolation of limited data from wells and seismic. Secondly a 'true ultimate' also depends on long-term future oil price, technology and demand, all of which cannot be known with certainty. Instead, 'URR', especially for a region, usually refers for most modellers to the quantity of oil judged likely to be extracted by some distant date. The latter is often not specified, but where specified can typically be 2070 or 2100, for example.

As noted, for a field or project the URR is simply the total amount of oil generated by the specific field or project when production stops. For a region, the URR also includes allowance for oil in *fields* that are yet-to-find (for conventional oil); and oil in prospective future *projects* (for non-conventional oil). Thus the equation for URR at a given date is:

URR = Cumulative oil production to-date

+ Proved-plus-probable reserves (i.e., the reserves remaining at this date) in discovered fields and in announced projects (whether in production or not)

+ Expected reserves growth (if any) over time in these fields and projects

+ *Fields* yet-to-find (if conventional oil)

+ *Projects* yet-to-include (if non-conventional oil).

A2.2 The need to differentiate conventional oil from non-conventional

Note: The following section is taken from Chapter 1 of Bentley (2016a).

In understanding the rise in oil price since 2004, and also the limits to future oil supply, an important distinction to make is between the production of *conventional* oil and that of *non-conventional* oil.

Oil exists in many forms. It can be found at the land surface or on the sea bed as oil seeps; in degraded form in tar pits and in extensive areas of tar sands; as oil's pre-cursor, kerogen, still in the original rock in which it was laid down (and from which it needs retorting to yield 'oil shale' oil); and as light, flowable oil, either still captured in the original rock (as 'shale oil', that needs hydraulic fracturing, 'fracking', to release it); or after having migrated to an open-pored reservoir of rock (an oil field), from which it can be extracted by drilling.

It is this last class of oil, *the relatively light, flowable oil in fields* that is generally classified as conventional oil, and where the bulk of oil production currently, and by far the largest part historically, has been of this class of oil.

By contrast, non-conventional oil tends to be found in extensive regions (within which there may be 'sweet spots'), and where flow to a production well is not possible without significantly changing the nature of the oil itself (for example, by heating to reduce viscosity, addition of a solvent, or retorting), or that of the surrounding material (such as mining the sand in which the oil is contained, or by fracturing the rock in which it is trapped). Non-conventional oil thus includes very heavy oil, oil from tar sands and Venezuela's Orinoco fields, shale ('light-tight') oil, and oil produced from kerogen by retorting.

Oil, in addition, can be produced from yet other sources. It can come from the physical transformation of some of the gas from gas fields, as either condensate or natural gas liquids (`NGLs`); by chemical transformation of gas from a variety of fossil sources (yielding gas-to-liquids, GTLs), or similarly from coal (coal-to-liquids, CTLs) or alternatively from biomass, either directly as biofuels, or by chemical or biological change from a variety of types of biomass.

As noted earlier, NGLs are often included in conventional oil, while the oil produced from GTLs, CTLs and biomass are often classed as 'other liquids'.

To see why this distinction between classes of oil is important, we need to ask the following question: Why over the last century and a half has the world, in the main, used conventional oil (i.e., oil in fields), rather than oil from the many other sources that exist, and where some of the latter (such as oil from biomass, and from coal and kerogen) were used extensively before conventional oil came to dominate?

The answer is simple: Up to now the oil in fields has usually been far cheaper to produce than these other oils. The reason for this generally lower cost of conventional oil relates principally to flow rate, and energy return.

A2.2.1 Flow rate

As noted above, oil in fields is concentrated geographically and flows easily, and hence often yields large flow rates when produced by relatively simple drive mechanisms, such as own pressure, gas-drive or water-flood.

For example, while the 1859 Drake well, the first commercial oil well in the US, yielded up to about 20 barrels of oil per day ('b/d'), only two years later the first major US gusher yielded 4 000 b/d, and in 1901the Spindletop field in Texas flowed at 100 000 b/d.

Admittedly in these early years such flows were often short-lived, but subsequent large fields typically have yielded over 500 000 b/d for considerable periods; while the Middle East giants produce 1 million b/d and above, and the world's largest field, Ghawar, averages over 5 million b/d. Thus once located, conventional oil from large oil fields has generally been cheap to produce due to relatively easy production methods and high flow rates.

As a result, while 'the petrol tank in your car does not care' what type of oil (conventional or non-conventional) is used, the user certainly does. The user would far prefer conventional oil at its pre-1973 long-term average real-terms price of $15/b, or even at its post-1985 real-terms average price (up to the 2004 increase) of $30/b, than to have to pay the ~$60/b production cost for much of US light-tight oil, or the more than $160/b for 'Canada oil sand mine upgraded' oil, currently estimated by IHS-CERA (see Figure 16 of Miller and Sorrell, 2014); or the production cost - whatever it will be - of retorted kerogen oil plus carbon capture, or of synthetic fuel made from electrolysis of water plus CO_2.

A2,2.2 Energy return

Another way to look at the relative ease of production of conventional oil is in terms of its energy return; nearly all of the non-conventional oils have lower energy returns. Though the data are hard to establish unequivocally, Guilford *et al*. (2011) and Hall (personal communication) suggest for example that the ratio of energy return to energy invested (EROI) for conventional oil was about 30:1 in the 1930s, rising to

40:1 in the 1970s as scale increased and technology improved, and subsequently falling with production of the more difficult conventional oils, such as deep offshore or Arctic oil, to an average ratio of perhaps 14:1 today.

By contrast, nearly all non-conventional oils have lower energy ratios; tar sands, for example, being quoted as having ratios of from 1.5 to 8:1, and corn ethanol as only perhaps 2 or 3:1 (probably higher in Brazil, and in some cases perhaps negative). Since Hall *et al*. (2009) and Lambert *et al*. (2014) calculate that modern society will have difficulty in functioning if its fuels have energy ratios of less than perhaps 5 – 10:1, the current transition from mainly conventional oil to increasing quantities of non-conventional oil is significant, and needs to be understood.

References

Aguilera, R. and Radetzki, M. (2016). *The Price of Oil*. Cambridge University Press.

Allix, P. and Burnham, A. K. (2012). "Coaxing Oil from Shale" (PDF). Oilfield Review (Schlumberger) 22 (4): 6. Retrieved 2012-04-18. (http://www.slb.com/~/media Files/resources/oilfield_review/ors10/win10/coaxing.ashx)

Attanasi E.D. & Root D.H. (1994). *The enigma of oil and gas field growth*. AAPG 78/3 March.

Bentley, R.W. (2015a). *Forecasting oil production using data in the BP Statistical Review of World Energy.* The Oil Age, Vol. 1 No. 1, pp 59-73.

Bentley, R.W. (2015b and c). *A Review of some Estimates for the Global Ultimately Recoverable Resource ('URR') of Conventional Oil, as an Explanation for the Differences between Oil Forecasts*. Part 1 in *The Oil Age*, 1(3) pp 63-90; Part 2 in *The Oil Age*, 1(4) pp 55-77.

Bentley, R.W., (2016a). *Introduction to Peak Oil*. Lecture Notes in Energy Vol. 34. Springer.

Bentley, R.W., (2016b). *A Review of some Estimates for the Global Ultimately Recoverable Resource ('URR') of Conventional Oil, as an*

Explanation for the Differences between Oil Forecasts. Part 3 in *The Oil Age*, 2(1) pp 57-81.

Bentley, R.W., Miller, R.G., Wheeler, S. and Boyle, G. (2009). *Comparison of global oil supply forecasts* - UKERC Review of Evidence on Global Oil Depletion: Technical Report 7. (Also see Annex1: *Models of global oil supply for the period 2008-2030.*) (www.ukerc.ac.uk & search 'TPA reports')

Campbell, C. J. (2013). *Campbell's Atlas of Oil and Gas Depletion*, Springer, 2nd Edition. [First edition (now out of print) was: Campbell, C.J. and Heapes, S. *An Atlas of Oil and Gas Depletion*, Jeremy Mills Publishing Ltd. UK, 2008].

Campbell, C.J., (2015). *Modelling Oil and Gas Depletion*. The Oil Age, Vol. 1 No. 1, pp 9-33.

Capen, E.C., (1996). *A consistent probabilistic approach*. SPE Reservoir Engineering, Feb., vol. 11 n°1.

Dale, S. (2015) *The New Economics of Oil*. Presentation to the Society of Business Economists Annual Conference, London 13th October 2015.

Guilford, M. C., Hall, C.A.S., O'Connor, P. and Cleveland, C.J. (2011). *A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production*. Sustainability, 3(10), pp 1866-1887.

Hall, C.A.S., Balogh, S. and Murphy, D.J.R. (2009). *What is the Minimum EROI that a Sustainable Society Must Have?* Energies, 2, pp 25-47.

See also: Hall, C.A.S., Lambert, J.G., Balogh, S.B. (2014). *EROI of different fuels and the implications for society*. Energy Policy. Vol. 64, pp 141-151.

Hubbert, M.K. (1949). *Energy from Fossil Fuels*. Science Vol. 109, February 4th, pp 103 - 109. This in turn notes that "'*Energy from Fossil Fuels*" was one of the papers presented as part of the Symposium on

Sources of Energy, held in Washington D,C., on September 15, during the Centennial Celebration of the AAAS [American Association for the Advancement of Science]'.

Hubbert, M. K. (1956). *Nuclear Energy and Fossil Fuels*. Drilling and Production Practice, pp 7-25; The American Petroleum Institute, 1956 (Note that for convenience we refer to the 'Hubbert 1956' method. This was clearly developed over a number of years, and Hubbert refers to earlier publications in 1948 and 1950. Similar remarks apply to the dating given for Hubbert's later works.)

Hubbert, M. K. (1962). *Energy Resources: A Report to the Committee on Natural Resources of the National Academy of Sciences - National Research Council*. Publication 1000-D, Washington DC, 1962.

Hubbert, M.K., (1967). *Degree of Advancement of Petroleum Exploration in United States*.

Hubbert, M K (1982). "*Techniques of Prediction as Applied to the Production of Oil and Gas*", Oil and Gas Supply Modeling: Proceedings of a Symposium at the Department of Commerce, Washington DC, June 18-20 1980; pp 16-141. [Report kindly supplied by Jens Junghans.]

Klett, T. R., D. L. Gautier, and T. S. Ahlbrandt. (2005). *An evaluation of the U. S. Geological Survey world petroleum assessment 2000*. AAPG Bulletin, 89:8, pp. 1033-42.

Laherrère, J. H. (2008). *Why are remaining oil & gas reserves from political / financial sources and technical sources so different?* Presented at the International Geological Congress, Oslo, 11th August 2008; and available from:

http://aspofrance.viabloga.com/files/JL-IGC2008-part1.pdf

http://aspofrance.viabloga.com/files/JL-IGC2008-part2.pdf

http://aspofrance.viabloga.com/files/JL-IGC2008-part3.pdf

Laherrère, J. H. (2011) presentation: *Backdating is the key* (http://aspofrance.viabloga.com/files/JL_ASPO2011.pdf).

Laherrère, J. H. (2015). *A Global Oil Forecasting Model based on Multiple 'Hubbert' curves and Adjusted Oil-industry '2P' Discovery data: Background, Description & Results. The Oil Age*, 1(2), pp 13-37.

Laherrère, J. H. (2016). Posting entitled: '*World, US, Saudi Arabia, Russia & UK oil production & reserves - Comments on Rystad 2016 world reserves*.' Posted 3rd August 2016. See also: http://aspofrance.org/files/JL_2016USoilultimate.pdf and http://aspofrance.org/files/JL_2016_California.pdf.

Lambert, J., Hall, C.A.S., Balogh, S., Gupta, A., Arnold, M. (2014). *Energy, EROI and quality of life*. Energy Policy, Vol. 64 pp 153 - 167. http://authors.elsevier.com/sd/article/S0301421513006447

Li S.Y., Ma Y., Qian J.L. (2011). *Global oil shale research, development and utilization today - and an overview of three oil shale symposiums in 2011*. Sino-Global Energy, 2012,17(2):8-17 (in Chinese)

Li S.Y.,Tang X., He J.L., Qian J.L. (2013). *Global oil shale development and utilization today - two oil shale symposiums held in 2012*. Sino-Global Energy, 18(1):3-11 (in Chinese)

Miller, R. G. (2012). *Reserves uncertainties: Fallow fields (and other questions)* ASPO conference, Vienna, May 2012. http://www.aspo2012.at/wp-content/uploads/2012/06/Miller_aspo2012.pdf

Miller, R. G. and Sorrell S. (2014). *The future of oil supply*. Phil. Trans. R. Soc. A **372**: 20130179.

Miller, R.G. (2015). *A Bottom-up Model of Future Global Oil Supply*. The Oil Age, Vol. 1 No. 2, pp 39 - 55.

National Petroleum Council (US). (2007). *Facing the Hard Truths about Energy – A Comprehensive View to 2030 of Global Oil and Natural Gas*

Petroconsultants Reports (1994 - 1996):

- *Undiscovered Petroleum Potential*. (1994). J. H. Laherrère, A. Perrodon and G. Demaison. Petroconsultants S.A., Geneva, 383 pp.

- *The World's Supply of Oil, 1930 - 2050*. (1995). C. J. Campbell and J. H. Laherrère. Petroconsultants S.A., Geneva, Oct. 1995, 650 pp; and on CD-ROM.

- *The World's Gas Potential*. (1996). J. H. Laherrère, A. Perrodon and C. J. Campbell. Petroconsultants S.A., Geneva, July/August 1996, 200 pp; and on CD-ROM.

And see also: Perrodon, A., Laherrère, J.H., and Campbell, C.J. (1998). *The World's Non-Conventional Oil and Gas*. The Petroleum Economist Ltd, London, March 1998; 113p; see http://textor.com/cms/dPEWNC.html

Qian J.L., Wang J.Q., Li S.Y. (2003). *Oil Shale Development in China*. Oil Shale, 20(3): 356-359.

Smith, M. R. (2015). *Forecasting Oil and Gas Supply Activity*. The Oil Age, Vol. 1 No.1, pp 35-58.

Sorrell S. and Speirs J. (2009). UKERC *Global Oil Depletion* report; Technical Report 1 (from TPA reports, www.ukerc.ac.uk) UKERC Review of Evidence on Global Oil Depletion. Data Sources and Issues. July 2009: REF UKERC/WP/TPA/2009/016.

[See also: Sorrell, S., Speirs, J., Bentley, R., Brandt, A., Miller, R. (2009). *Global Oil Depletion - An assessment of the evidence for a near-term peak in global oil production*. Technology and Policy Assessment report: UK Energy Research Centre, August 2009. ISBN 1-903144-0-35 (Go to: www.ukerc.ac.uk & search 'TPA reports').]

Sorrell S, and Speirs J. (2014). *Using growth curves to forecast regional resource recovery: approaches, analytics and consistency tests*. Phil. Trans. R. Soc. A **372**: 20120317.

Thompson, E., Sorrell, S., Speirs, J. (2009). UKERC Review of Evidence on Global Oil Depletion Technical Report 3: The Nature and Importance of Reserve Growth July 2009: REF UKERC/WP/TPA/2009/018

USGS (2000). U.S. Department of the Interior. U.S. Geological Survey World Petroleum Assessment 2000 – Description and Results. T.

Ahlbrandt *et al*. U.S. Geological Survey Digital Data Series - DDS-60. (Available on CD-ROM, from: http://pubs.usgs.gov/dds/dds-060)

Wold, E. (2015). Bottom-up Modelling of Future Global Oil Supply and Associated Spend. *The Oil Age*, 1(4) pp 19-39.

Zhu J., Che C.B., Zhang D.Y. (2012). *Status and prospects of oil shale exploration and development in China*. China Mining Magazine, 2012, 21(7):1-4 (in Chinese)

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