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Global Oil Production – Forecasts and Methodologies

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Abstract

A range of forecasts of global oil production made between 1956 and the present day are listed. For the majority of these the methodology used to generate the forecast is described. The paper distinguishes between three types of forecast:

- Group1: quantitative analyses that predict global oil production will reach a *resource-limited* peak in the near term, and certainly before the year 2020;
- Group2: forecasts that use quantitative methods, but which see no production peak within the forecast's time-horizon (typically 2020 or 2030);
- Group 3: non-quantitative analyses that rule out a resource-limited oil peak within the foreseeable future.

The paper analyses these forecast types and suggests that Group 1 forecasts are the most realistic.

Introduction

This paper describes some of the methodologies used to predict world production of oil. The models fall into three broad groups, depending on how the authors saw, or see, the future of global oil production:

Group 1 forecasts predict that global oil production will reach a resource-limited maximum ('peak') sometime between the years 1996 and 2020, and thereafter decline. Some of these forecasts refer to the production of conventional oil only, others to the production of all-oil (conventional and non-conventional oil combined), and some to the production of all hydrocarbons (all-oil plus all-gas).

Group 2 forecasts predict 'business-as-usual'. These assess the oil resource base as fully sufficient to meet anticipated demand growth to either 2020 or 2030, the dates at which these forecasts end. Group 2 forecasts do not say if a resource-limited peak is expected subsequently.

Group 3 analyses use theoretical grounds to rule out the possibility of a resource-limited oil peak in the near or medium term. Such analyses see no need to assess world future oil production in quantitative terms.

Methodologies underlying these forecasts are discussed below. Some Group 1 and Group 2 forecasts are summarised in Tables 1 and 2.

I: The Data and Modelling of Group 1.

1. Hubbert, 1956 – 1977 Forecasts.

From 1956 to 1977 the geologist M.K. Hubbert published a series of seminal papers describing methods by which the date of a region's resource-limited peak in the production of oil could be estimated (Hubbert, 1956, 1962, 1982). In summary, these methods were:

- 1956: Peak date derived by combining an industry estimate of a region's original endowment of recoverable oil with a hand-drawn production curve. (A region's original endowment of recoverable oil, i.e., its ultimately recoverable reserves, is generally termed the region's 'ultimate').

- 1962: Peak date derived from historical data on proved discoveries, proved reserves, and past production; combined with a logistic curve to estimate ultimate. Also ultimate derived from field distribution by size and number. For large fields these were 'grown' (their size increased to allow for conservative initial reporting), and these increases backdated to the original date of discovery.

- 1967: Detailed examination of grown backdated discovery data. Also, generation of an estimate for ultimate from grown backdated discovery per foot drilled.

- 1969: Use of two estimates for the world ultimate (1350 Gb, and 2100 Gb) combined with logistic-derivative production curves.

- 1977: Use of Nehring's estimate of 2000 Gb for the world ultimate.

More details on these models are given in a longer version of this paper available from the authors.

2. Hubbert's 1982 paper

In 1980, at a Department of Commerce symposium Hubbert gave an overview of the methods he had developed. The resulting paper (Hubbert, 1982) is an excellent summary, and covers a great deal of ground.

Hubbert first examined the 'geologic' (intrinsic basin rock 'oiliness') method for estimating ultimate, and showed that this is of little use as oil richness can vary by a factor of 100 between basins and there is no way of knowing this factor before exploration is significantly advanced.

He then looked at the typical complete cycle of oil production in a region, and emphasised that: "There is no necessity that [production has] a single maximum, or that it be symmetrical. In fact the smaller the region, the more irregular the shape of the curve ... For large areas, such as the entire United States or the world ... the irregularities of small areas tend to cancel ... and the curve becomes a smooth curve with only a single principal maximum." But he notes that even such a 'large-region' curve need not be symmetric.

He then presented the mathematics to derive the production cycle curve from primary data. This followed from his earlier discovery that the logistic curve was a good fit to US data, but here he derives the logistic curve from a simple assumption on the shape of production vs. cumulative production. He put this in the form of a simplified linear relationship by plotting production divided by cumulative production against cumulative production. This turns the logistic curve into a straight line that intersects the abscissa at the value for ultimate.

He then re-presented the 1962 method for determining peak that uses simply historical production, proved reserves and proved discoveries data. The additional data available by 1982 extended the curves considerably from the original 1962 analysis, and with the US peak then well past, confirmed the correctness of that analysis. It is crucial to note that in using US proved reserves Hubbert stressed that these represent "oil in existing fields that has been proved by development drilling and is recoverable by existing installed equipment and technology. [It] is a conservative figure and is not intended to represent the ultimate amount of oil that known fields will produce."

He then also reprised a third method for determining ultimate and peak, based on discoveries per cumulative feet drilled. Here he re-examined the methods by which future increases in field size can be estimated, so that 'grown' (and backdated) data can be used in this 'discovery-per-cum.-ft.' method. Again, the updated data available in 1980 confirmed the dramatic fall-off in US 'true' oil discovery since the 1930s that he had reported in 1967.

The paper finishes with a report of the follow-up discussion. The latter is particularly revealing. Hubbert again stressed that the production curve need not be symmetric; he stated explicitly that his studies were of conventional oil, excluding "oil shale, coal, and the Orinoco heavy oil"; he recognised the scope for increased recovery but noted that "the effect may be easily exaggerated"; and in terms of increased recovery he brought in the notion that energy content vs. energy for extraction sets a physical limit on what will be extracted for energy use. Finally, and perhaps most importantly, he addressed the issue of the effect of oil price in increasing oil supply. He said: "During the last decade we have had very large increases in the

monetary price of oil. This has stimulated an accelerated program of exploratory drilling and a slightly increased rate of discovery, but the discoveries per foot of exploratory drilling have continuously declined from an initial rate of about 200 barrels per foot to a present rate of only 8 barrels per foot.”

Elsewhere Hubbert noted that “Methods based on this type of analysis, which have been developed and used by the present author during the last 25 years, have consistently given predictions of the future course of oil and gas production in the US which have agreed within narrow limits with what has subsequently occurred”.

In summary, with data and help from others, Hubbert introduced powerful new methods for predicting the oil peak date for a region. That he did so in a country where reserves data were (and are still) so misleading, and at a period - largely because of these poor data - in which the then-imminent oil production peak was nearly unrecognised is an outstanding testament to the man’s ability.

3. Other estimates from the 1970s and early 1980s.

In the 1970s and early 1980s a variety of groups forecast the date of global oil peak, probably in some (or even most) cases using either Hubbert’s own findings, or his general methodology. These forecasts included:

- ESSO used an ultimate of 2100 Gb to expect: “oil to become increasingly scarce from about the year 2000”, (*The Ecologist*, 1972, pp 18 and 130).

- B. Ward and R. Dubois, in a landmark environmental report to the United Nations, said: “One of the most quoted estimates for usable reserves [of oil] is some 2500 billion barrels. This sounds very large, but the increase in demand foreseen over the next three decades makes it likely that peak production will have been reached by the year 2000. Thereafter it will decline”, (Ward and Dubois, 1972, p184).

- The UK Department. of Energy, in commenting on the expected date of the UK peak, noted that the world peak would not be far behind, at: “about [the year] 2000.” (UK Dept. of Energy, 1976, p12).

- P. Ehrlich *et al.* calculated the global oil peak date at the year 2000 based on their ‘high-estimate’ for conventional oil endowment of 10,900 trillion MJ (~ 1900 Gb), (P. Ehrlich *et al.*, 1977, pp 400-404).

- Shell in 1979 expected oil production to: “plateau within the next 25 years.” However, they did not specify the data behind this forecast. (Shell, 1979, p 1)

- The World Bank, on the back of an ultimate of 1900 Gb, expected oil to “plateau around the turn of the century.” (World Bank, 1981, p 37, 46).

A number of other authorities at about this time also gave estimates for size of the global oil ultimate but did not carry these through to predictions for the date of peak. These included:

- The Science Policy Research Unit (SPRU) at Sussex University, which gave a range for the world oil ultimate as 1800 - 2480 Gb, (Cole *et al.*, Eds., 1974).

- The World Energy Conference (WEC, now the World Energy Council), whose Commission report included a Petroleum Resources and Production study by the Institut Français du Pétrol. This estimated the world oil ultimate as 1803 Gb. In commenting on this WEC/IFP study, J. Keily noted presciently: “The world can have the energy it needs for the rest of the 20th century. But ... with a false sense of security, many will not look over the horizon to the early part of the 21st century. ... It is only by looking beyond the early 2000s that we can see how fast the change will come.” (J. Keily, 1980, pp 26 - 32.)

- D. Meadows *et al.* in *Beyond the Limits* (sequel to *Limits to Growth*) quoted the range for the world’s oil ultimate as 1800 - 2500 Gb (D. Meadows *et al.*, 1992). No forecast for date of peak was given; the group perhaps not aware of the serious implications of combining these data with a ‘decline from the mid-point’ model.

4. H.R. Warman

Harry Warman within BP modelled future oil production, based almost certainly on a ‘mid-point’ approach. His 1979 report *Oil Crisis ... again?* predicted that world oil production outside communist areas would peak about 1985 (Warman, 1979). This report has been widely cited by critics such as Peter Odell, John Mitchell, and Vaclav Smil as proof of the inability of ‘fixed resource’ models to forecast oil production. Closer examination however reveals that Warman’s data on the size of the non-communist non-NGL recoverable oil resource were reasonable. The problem, just as with Hubbert’s prediction for the global peak in 1996, was that Warman assumed unfettered growth toward peak, and did not factor-in the global demand reductions of the 1980s.

5. Petroconsultants, 1994 - 1996.

In 1994 and 1996 Petroconsultants S.A. (now IHS Energy) produced consultancy reports that used a ‘petroleum system’ approach (source rock, burial history, migration, reservoir and seal) to estimate ‘ultimates’ of the world’s main petroleum systems for oil and gas.

In 1995 Petroconsultants produced a report which generated assessments of individual oil ultimates by country, and calculated the consequent rates of future production. This report was a landmark in that it used an industry dataset and extensive geological knowledge to generate detailed by-country resource and production modelling.

For this 1995 report, the general methodology was as follows:

- Estimation of ‘P50’ oil reserves by country. (‘P50’ reserve estimates are those with a notional 50% probability of being correct). These estimates were generated by taking ultimately recoverable reserves (‘URR’) data from the Petroconsultants’ database, but adjusting them in the light of the authors’ extensive geological knowledge, and on the basis of reasonableness tests. A key test was to plot field production vs. cumulative production. This linearises exponential decline, and for most fields where decline is underway provides a good indication of the field’s likely URR. This approach showed, for example, that many field reserves in the former Soviet Union were significantly over-reported.

- Generation of estimates of oil yet-to-find. This analysis mostly used a range of statistical approaches, largely based on discovery data to-date, to estimate the quantities of conventional oil likely be found in the region within a reasonable exploration time-frame (for example, from twice as many wildcats as already drilled). The techniques included plotting regional ‘creaming curves’ (plots of cumulative discoveries vs. new-field-wildcats); and the use of a parabolic fractal plot, developed by Laherrère (see below), of field size vs. rank, and examining the development of this plot over time. Estimates of yet-in-the-ground were evaluated in the light of geological knowledge, and converted into yet-to-find based on simple assumptions of drilling capacity.

- For each country addition of its cumulative production, P50 initial reserves and to yet-to-find gave an estimate of that country’s ultimately recoverable reserves (‘ultimate’).

- Modelling each country’s future production. For a country already past peak, this simply declined future production at the existing depletion rate (fixed percentage of the remaining recoverable resource). If prior to peak, the forecast increased production at an assumed growth rate until cumulative production equalled half that country’s ultimate, and thereafter decreased production at the depletion rate at peak. In the case of the Middle-East swing producers, production was calculated under a number of assumptions subject to each country’s resource limits.

6. L.F. Ivanhoe

In an article in *World Oil* Ivanhoe (1996) used the fact that for many regions the shape of the production curve tends to ‘mirror’ the shape of the discovery curve. For the world, using smoothed discovery data quoted by the US Geological Survey (USGS) -- almost certainly, Petroconsultants’ data originally -- Ivanhoe employed the technique to predict the date for the global conventional oil peak to be about 2010. Ivanhoe’s article constituted a clear and well-written warning of the global conventional oil supply problems to come. For comments on using this ‘mirror’ approach, see Section II.

7. IEA: *World Energy Outlook, 1998.*

The International Energy Agency, in its *1998 World Energy Outlook*, based its 'Reference case' on an estimate of the global conventional oil ultimate of 2300 Gb; which was the same as the median estimate (excluding natural gas liquids, NGLs) in the USGS 1994 World Assessment. The IEA calculated the date for the world conventional oil peak as 2014, probably by combining this ultimate with the mid-point peaking argument (IEA, 1998).

To meet projected world demand beyond this date, the IEA indicated the need to include unconventional oil in "identified" projects, plus a rapid rise in the supply of "unidentified unconventional oil". Sources within the IEA have since indicated that this terminology was chosen to highlight the difficulty of getting supply to meet anticipated 'business-as-usual' demand. The IEA also modelled a lower ultimate of 2000 Gb; and a higher one of 3000 Gb,

This 1998 report was the IEA's first modelling (at least perhaps since the 1970s) that took the physical reality of 'mid-point' peaking' into account. The IEA had difficulty in getting this view accepted internally, and subsequent *WEO's* presented a more optimistic message both on the size of ultimate, and on the scope for technology to increase recovery rates, see 'Group 2' modelling below.

8. BGR, Germany

The German government's Federal Institute for Geosciences and Natural Resources (BGR) prepares every four years a report entitled "Reserves, Resources and Availability of Energy Resources". This is based on all publicly available information and on internal government papers. In the edition reporting for 2001/2002 (BGR 2002) the oil depletion mid-point was estimated to occur in the year 2017. This estimate was a static approach considering the then-known global EUR (ultimate) of conventional oil of 2670 Gb (364 Gt), the relevant depletion mid-point (182 Gt), the reserves of conventional oil 1113 Gb (151.8 Gt), the resources of conventional oil 616 Gb (84 Gt), and the consumption in 2001. Note that the BGR defines conventional oil as including light oil from all areas worldwide, as well as NGLs.

9. K.S. Deffeyes

In his 2001 book updated in paperback in 2003, Deffeyes applied the Hubbert logistic curve linearisation technique to oil production data from a variety of countries, and for the world. For the world the plot indicated that oil production "will probably reach a peak sometime during this decade" (Deffeyes, 2003). Additionally, he noted that the peak might already have occurred in 2000, driven by the approaching resource limits and by Middle East geo-political issues.

Deffeyes also models *discovery* data on the same linearised plots. In 2003 for global discovery he applied some of the OPEC 'quota wars' adjustments highlighted by Campbell and Laherrère and originally pointed out to them by Ivanhoe. (These adjustments, made by several OPEC nations, involved arbitrary increases in their claimed oil reserves, in order to permit increased production under the OPEC reserves-based quota system.) However, for these calculations Deffeyes has no direct access to industry datasets.

In his later book, Deffeyes (2005) updated these plots, and found the global peak as likely in 2005.

10. P-R. Bauquis

Pierre-René Bauquis is a TOTAL Associated Professor who worked at a senior level in that company for many years. He assumed a global ultimate (including NGLs) of 3,000 Gb to predict that the global liquid hydrocarbon peak will occur in 2020, at a rate of 95 Mb/d. It is believed that this figure for 'ultimate' is based, at least in part, on the estimate from Laherrère, and thus includes non-conventional oil.

11. C.J. Campbell & A. Sivertson ('Campbell-Uppsala' model)

Over successive years Campbell has updated the 1995 Petroconsultants study (later adapted and partly incorporated into *The Coming Oil Crisis*, published by Multi-Science and Petroconsultants) as new data became available. He changed the definitions and calculations somewhat, being more explicit about categories of oil modelled, and how NGLs are treated. The non-conventional supply was now included, with production assumed to ramp up roughly in line with announcements to about 2010, and thereafter at a steady but not dramatic pace.

In 2002 Campbell had the able assistance of Sivertson of the University of Uppsala to upgrade the model, and to tidy up obscurities that had crept in over the years. The result was the 'Campbell-Uppsala model (Campbell and Sivertson, 2003). This finds that global demand can be met by the 'all-liquids' supply (conventional plus non-conventional oil, plus NGLs) up to 2010, with supply falling to some 25 Mb/d below demand by 2020.

In 2004 the model was updated yet again as follows:

(a). The Five Middle East countries, previously considered to have a "swing role" making up the difference between world demand and what the other countries could produce, were now considered to have negligible spare capacity (partly because they may have been reporting total discovery not remaining reserves, and partly because of the difficult political situation following the Anglo-US invasion of Iraq). Accordingly, their production was modelled to be on average flat to their individual depletion midpoints, reflecting a volatile world environment of alternating oil price shocks and consequential recessions, dampening oil demand and reducing pressure on price.

(b). As previously, production was assumed to decline at current depletion rates (annual production as a percentage of what is left) in countries past their depletion midpoint. Production was assumed to be flat in countries not yet at midpoint or as otherwise indicated by local circumstances, but this assumption is not very critical as most such countries are now modelled as being within only a few years of midpoint.

12. A. Bahktiari

Bahktiari and colleagues, working in association with the National Iranian Oil Company, have generated an oil modelling methodology ('WOCAP'), and used it to forecast Middle East production by country, and also world production. Bahktiari stresses that this model does not represent an official NIOC view (Bahktiari, 2001).

In an article in the *Oil & Gas Journal* in 2004, Bahktiari and his group use the latest updates on Saudi and Russian reserves to conclude that "The World oil production capacity model suggests the output peak by 2006-7", at about 81 million barrels per day.

13. J.H. Laherrère

Laherrère, like Campbell, has been very active in global oil and gas modelling since his participation in the Petroconsultants 1994-1996 reports. His main contributions have been very comprehensive analyses of field and region depletion; and analyses of the extraordinary discrepancies that exist between the various oil datasets.

In addition, he has put effort into modelling production as a 'mirror' of discovery, using multiple logistic curves when discovery in a region occurred in phases, and modifying reported discovery data when dictated by detailed field analysis; see, e.g., Laherrère (2004).

In terms of estimating a world 'ultimate', Laherrère now puts this at about 3 Tb. Laherrère, probably more than anyone else, knows how uncertain are the numbers, and also how uncertain which of the various possible non-conventional oils, and oil substitutes, are likely to yield useful volumes on a world scale. He is reluctant therefore to break this 3 Tb estimate into components; but a reasonable guess would be: 2.0 Tb for conventional oil, 0.3 Tb for NGLs, 0.3 Tb for tar sands, 0.3 Tb for Orinoco and other very heavy oils, and 0.1 Tb for refinery gains and GTLs (gas converted to liquids) .

14. Energyfiles Ltd.

Energyfiles use historic discovery and production data for all liquid and gaseous hydrocarbons derived from a wide variety of public domain sources. These are combined with independently determined yet-to-find resources based on geoscience and engineering principles, allied to exploration experience in most countries of the world and contacts with oil companies and governments.

Modelling is individually carried out for all countries in the world that produce significant oil and/or gas volumes. Future production capacity estimates are based on judgemental country-by-country analysis using individual growth and decline curves that meet exploration, engineering and economic constraints. The curves inherently calculate total reserves and resources ('ultimates'), and do not use simple 'mid-point peaking'.

The global summary for oil in the Energyfiles reports shows differing estimates of OPEC restriction in the years to peak for four demand growth scenarios (zero - 3%). Production from conventional, deepwater, gas condensates and tar sands is included as oil. Country profiles are combined to give views on the limits to global oil production and the viability of alternatives that may be developed over coming years.

Energyfiles estimates the conventional oil global 'ultimate' including NGLs as 2,338 Gb and concludes that the world's known and estimated yet-to-find reserves and resources cannot satisfy the current level of production of 75 million barrels per day beyond 2020. Growth in demand averaging 1% per year brings forward the peak year to 2016. Energyfiles' view is that even with the Middle Eastern countries producing as much as they can - inevitably requiring major foreign investment - forecasts of demand requirements of anything over 90 to 100 million barrels per day cannot be met.

15. R. G. Miller (BP)

BP's Richard Miller is one of the few modellers currently calculating forward global production on a detailed field-by-field basis. His model is produced within BP, and circulated among some senior managers, but is 'unofficial', and does not represent a BP view. In Miller's model about 70% of global production is accounted for by individual fields, 15% is aggregated by State, province or basin (respectively in the USA, Canada - excluding oil-sands - and China), and the remaining 15%, which comes from small or poorly documented fields, is aggregated by country as "other production". The model uses a variety of primary data sources, including the published *Oil and Gas Journal* field database, the commercial Wood Mackenzie and IHS databases, internet searches and primary published data from government agencies and oil companies. Most types of oil are included, including deep-water, Canadian oil sand 'syncrudes', and condensate, although some large condensate fields are excluded by the *Oil and Gas Journal*.

The model makes a very small allowance for future increased recovery by technical improvement, modelling this globally as 0.2% extra production in 2005, 0.4% extra in 2006, and so on.

The model extrapolates oil production out to 2030, using historical and current field production rates, observed rate changes, remaining field reserves estimates and national yet-to-find estimates. The yet-to-find estimates are not independently obtained but culled from various sources including Campbell and the USGS, but checked and adjusted against exploration results over the past five years. For most countries, a percentage of the yet-to-find oil is assumed to be discovered annually, that percentage decreasing steadily with time; Middle East OPEC countries are treated separately. The model assumes that all discoveries are developed, and that the soonest that any new oil discovery could be brought into production is between 2 years (e.g. for small fields adjacent to existing infrastructure) and 7 years.

Experience with the model over some years shows that the greatest discrepancy between prediction and eventual reality is the timing of new discoveries coming on-stream. Many discoveries are not developed for commercial reasons as soon as they might otherwise be, so actual production has always been somewhat less than forecast. Consequently,

the timing of the global peak of production has been continually postponed, although the original estimate of yet-to-find oil has not so far needed major adjustment (Miller, 2004).

16. PFC Energy

PFC Energy recognised that their long-standing forecasting process, while good at assessing new projects coming on-stream, was not accounting adequately for decline in existing fields. The company decided therefore to build a detailed bottom-up global model.

The company takes backdated industry data on 'proved plus probable', or '2P', reserves (roughly equivalent to 'P50' reserves) from a number of sources including IHS Energy, and compares these to arrive at best-judgment reserves estimates. They pay particular attention to reserves for the FSU and Middle East, though admit that data for these regions remain problematic. Like most others with access to '2P' industry data, PFC Energy judge the Middle East 2P reserves to be 'smaller' than the public-domain proved ('1P') reserves.

For near-term future projects they use the company's recognised expertise in fiscal modelling to judge prospective project likelihood vs. various threshold levels. For longer-term 'yet-to-find' they combine extrapolated field-size distribution curves with in-house expertise, and with consideration of commercial thresholds, to generate a range of possible 'yet-to-find' values.

Plots of future oil production are then produced by country or region, but PFC Energy also make extensive use of modelling of current and future production of individual fields where these are significant in size, and in other instances where this level of detail is justified.

A key aspect of PFC Energy's modelling is that it incorporates sensitivity analysis to reflect ranges for reserves size, future improvements in recovery factor, and change in oil price. The size of these ranges are arrived at on the basis of historical experience and modelling judgment rather than analytically; and are plotted as a suite of future production curves running from P95 (95%) to P5 (5%) probability. For the Middle East, political factors such as anticipated quota access and National Oil Company policy are also included. The forecasts include NGLs and non-conventional oil production.

PFC Energy are currently undertaking a range of additional studies, including non-conventional oils and gas. These will help firm-up their conclusions for the date of the global 'all-liquids' peak (including non-conventional oils). For their base case scenario, this 'all-liquids' peak is calculated as occurring in 2018 (PFC Energy, 2005).

II. Issues Raised by Group 1 Modelling

(a). Including the Effects of Oil Price and Technology Advancement.

Today the mechanism that drives the oil peaking process is well understood. Larger fields tend to get into production first, and once the discovery of new fields has slowed, production from the succession of smaller fields is insufficient to offset the declines in the early fields. For a region where discovery has slowed, combining the extrapolated 2P discovery data with geological knowledge gives a reasonably accurate estimate of the amount of oil to be produced in that region over the medium term. This in turn sets a limit to the region's future production curve. Such calculations now show that more than 60 of the world's 100-or-so oil producing countries are past their conventional oil production peak.

The primary determinant of future potential production (and often of production itself when quotas etc. are absent) - once discovery has slowed - is thus the quantity of oil already discovered. Price and technology are then generally only second-order drivers of future production, as Hubbert pointed out over half a century ago. For this reason, given the closeness of the predicted date for peak, Group 1 modellers tend to be more concerned by the large uncertainties in 2P discovery data for the FSU and Middle East, than by potential price or technology developments. Nevertheless if oil forecasting is to be accurate as possible, it should aim to include anticipated changes in both technology and price.

(Incidentally, it was partly because these factors were omitted from early Group 1 models that Group 3 analysts paid such scant attention to their forecasts. Technology gain often was, however, partly included as methods which 'grow' fields based on historical data

implicitly incorporate such advances. Too often, though, analysts have confused real technology-driven growth with the usually much larger reserves increases caused by conservative 1P ‘financially committed’ proved reserves moving towards the 2P values as the fields were developed.)

(b). Rate of Availability of Non-Conventional Oils

Some Group 1 models include the rate at which non-conventional oils are likely to come on-stream. However, these rates are based on current views, and not driven by fundamentals. Humankind is indeed ingenious, and high oil prices will encourage a wide variety of new oils and oil substitutes onto the market. Fundamental constraints of cost, net-energy, investment, pollution and societal pressures will set limits to the rates at which these energies can be deployed, and detailed analysis is needed to calculate these limits, see Bentley (2006).

(c). Other Technical Issues

On a technical level, it is useful to examine the extent to which regional discovery and production follow a logistic curve, and whether production peaks occur at close to 50% of the ultimate. These topics are covered in the longer version of this paper.

(d). Evolution of the models

Note that there has been an important evolution over time in the methods used for Group 1 forecasts. The early forecasts were based on an estimated global ‘ultimate’ and an assumed future production profile; the latter sometimes following the ‘Hubbert’ curve. Later forecasts used a variety of methods, including linearisation of the production curve (assuming that future production would follow a Hubbert curve); the assumption that future production ‘mirrors’ past discovery; and use of an estimate for ultimate coupled with a non-Hubbert expected production profile.

However most of the recent forecasts within Group 1 make no estimates for ultimate, but simply sum the expected production from known and anticipated fields or regions. This approach is now appropriate simply because the expected oil peak is so close that virtually all the fields that will determine this peak are already discovered, and the vast majority of these already in production.

III. The Data and Methodologies of Group 2

We now turn from Group 1 models to the ‘business-as-usual’ models in Group 2.

1. WEC / IIASA, 1998

A study from the World Energy Council (WEC, 1998) used oil resource data from the International Institute for Applied Systems Analysis (IIASA) to show that no peak would occur at least before 2030. Unfortunately, IIASA have no great petroleum resources expertise. For example, a list of global reserves and resources they produced did not differentiate between proved and 2P reserves, nor comment on the very poor data in the former. In this respect IIASA is, however, no more ignorant than many other recognised bodies in the field.

2. IEA: *World Energy Outlook 2000*

The IEA's *World Energy Outlook 2000* (IEA, 2000) used the USGS 2000 assessment of a mean 3345 Gb oil ‘ultimate’, where this included NGLs and reserves growth. This number assumes large reserves gains from the future application of technology, even though the USGS figure was based on the notion, one that the USGS themselves raised as unresolved, of whether past ‘reserve growth’ in the US could be extrapolated to other parts of the world. (C. Masters, leader of the USGS team for the previous two surveys, had decided against including a large allocation for reserves growth outside the US.)

Furthermore, the IEA stated that the USGS data were ‘authoritative’, omitting to point out that these data are assessments of yet-to-find, and do not address the issue of *rate* at which this oil can be discovered and produced.

On the basis of these data, the IEA said that adequate reserves existed for global production to meet demand up to their forecast horizon of 2020. It is entirely possible that in this calculation the IEA forgot principle of resource-limited production peaking which they recognised in 1998, and naively compared the total volume of reserves and yet-to-find with the amount of oil required to meet production up to 2020.

In this and subsequent *WEO*’s other serious technical errors by the IEA have included confusing proved 1P reserves with 2P reserves; and identifying very large technology-driven reserves growth in the North Sea, where this was based on changes in the 1P data, as opposed to the relatively modest quantities of 2P growth that actually occurred.

It may have been the loss of Bourdairé, Wigley and Miller, or the arrival of Appert (formerly Deputy Director General of the Institut Français du Pétrol) with the latter’s emphasis on technology, or the political pressure of the USA and Canada, which caused the transition from the ‘peaking’ view given in the 1998 *WEO*. The latter two countries had opposed that report’s gloomy message on oil nearly as much as they opposed the view that gas production was about to peak in North America; intervening so that the IEA’s report was softened on the latter issue.

3. Shell Scenario Modelling

Shell’s scenarios are widely quoted. Shell’s recent global ultimate of 4000 Gb is composed of: ~2300 Gb of conventional oil (incl. NGLs); ~600 Gb of ‘scope for further recovery’ (‘SFR’) oil; plus 1000 Gb of non-conventional oil. Shell therefore envisages that the unconventional oils will come on-stream smoothly as conventional oil declines.

4. US EIA, 2001

The US EIA 2001 modelling used the USGS 2000 mean ‘ultimate’ for conventional oil (excluding NGLs, but including reserves growth) of 3003 Gb (EIA, 2001). Their analysis then showed that with this ultimate, if the world decline rate is taken as 2% p.a., the peak is at 2016. If a much steeper, unrealistic, decline rate of 10% p.a. (corresponding to the US 1P reserves-to-production ratio of 10) is assumed, this puts the peak later, at 2037. See the comments on this approach in Bentley, 2002.

As with the IEA 2000 *World Energy Outlook*, this study uses USGS 2000 survey results in an uncritical manner, both on the rate of discovery of oil, and on the scope for reserves growth outside the US. From discussion with the EIA’s John Wood it may be that he sees this modelling more as exploratory calculations, rather than defensible detailed analysis. His underlying opinion seems to be that proper application of current technology can recover very large amounts of extra oil from existing fields.

5. EU ‘WETO’ study, 2003.

This is another recent study that uses USGS year-2000 assessment data at face value (EU, 2003). The study was funded by the EU’s DG-Research, and incorporates the POLES model. The study uses a high USGS estimate (of 2800 Gb) as its starting value for world URR (i.e., ultimate), and then builds in a time-dependent process of reserves growth on top to yield an extraordinarily high assumed global conventional oil ultimate of 4500 Gb by 2030. To set the latter figure into context, see the commentary below.

The POLES model then ties production to price-dependent R/P ratios. The methodology thus ignores realistic values for either the URR, or for rates of discovery and recovery improvement; as well as the long empirical evidence of regional ‘decline from the midpoint’. It is unlikely that the group has tried its predictive methodology on any of the countries or regions that have already gone over conventional oil resource-limited peak. The authors state in conclusion that “sufficient oil reserves exist to satisfy the projected oil demand over the next three decades”; with the latter reaching 120 Mb/d by 2030.

6. ExxonMobil, 2006.

ExxonMobil annually updates its *World Economic and Energy Outlook*. We do not know how the company does its modelling, but it recently placed an advertisement (March 2006) headed: “Peak Oil? Contrary to the theory, oil production shows no sign of a peak.” This cites improvements in extraction technology, and says: “Because of such technology gains, estimates of how much recoverable oil remains have consistently *increased* over time.” (Exxon’s italics).

This statement reflects either overlooking the fact that the USGS 2000 survey included reserves growth whereas prior surveys did not, or a poor understanding of the size of technology-driven change in 1P or 2P reserves data. If the latter is the case, the company needs to look at recent IHS analysis of reserves growth in their 2P database, see Bentley (2006). Misunderstanding the real effect of technology gain on the world’s reserves probably indicates a lack of oil peak modelling expertise within the company. The company would be advised to look in detail at the increasing number of countries going past peak, and develop a model that captures the underlying processes.

7. IEA, *World Energy Outlook 2005*

In 2005 the IEA issued its latest *World Energy Outlook* (IEA, 2005), focussing particularly on oil supply from the Middle East and North Africa (MENA) region.

For its *Reference Scenario*, MENA oil production is simply assumed to fill the gap between total world demand and the sum of non-MENA plus non-conventional oil production. This follows the IEA’s historical approach of modeling supply by equating it to demand, based essentially on the assumption that investment can always turn sufficient ‘resources into reserves’. It is true, however, that the IEA’s supply-side approach has become more sophisticated over time, and in this *Outlook* the calculations of potential MENA supply use data drawn from field-by-field analyses of the large fields in the region based on IHS Energy data. To meet world demand to 2030, the calculations have to assume adequate new fields and recovery gains. To put these projections into context, this scenario assumes for example that Saudi Arabian production climbs to 18 Mb/d by 2030; a figure that at least one senior ex-Aramco individual has said is unrealistic.

In its *Deferred Investment Scenario*, the IEA’s *World Oil Equilibrium Model* solves for the equilibrium oil price that adjusts both MENA and non-MENA oil to equate world supply with demand. Here technology improvements, and supply gains with price, are variables that can be set within the model (albeit in some cases based on historical trends), so it is almost certainly difficult in such modeling to properly incorporate the constraints set by physical limits to extraction rate. The IEA states that the non-MENA supply so calculated fits within the countries’ resource estimates, but the question has to be asked whether here the *resource-limited production level* of non-MENA supply has been considered, or just naively the total volume of reserves. This is because the IEA’s model in this *Deferred Investment Scenario* has non-MENA conventional oil production rising from 51 Mb/d in 2004 to over 58 Mb/d in 2030 (Table 7.5). This increase conflicts with the modeling detailed elsewhere in this paper that generally has non-OPEC conventional oil as already at, or close to, decline.

IV. Commentary on Group 2 Models

The main criticism of ‘Group 2’ models is that they largely ignore the reality set by the oil industry’s geological 2P discovery data, and by current knowledge of the scope for recovery improvement. For example, the EU ‘WETO’ study’s value for the global conventional oil ultimate of 4500 Gb must be set against the fact that today, after 150 years’ of exploration and technology improvement, only about 1950 Gb have been discovered. In bridging the gap between 1950 Gb and 4500 Gb the WETO study must recognise that global 2P oil discovery peaked long ago in the mid-1960s, and that oil in new fields is now being discovered at less than 10 Gb/year on a declining trend. The WETO study clearly does not understand that discovery history data drive the peak.

For comments on using the USGS year-2000 Assessment data at face value to model future production see e.g., Laherrère (2000), or Bentley (2002).

Particular remarks must be made about the IEA. Set up in the wake of the 1970s shocks with a remit to help forewarn the world of future shocks, the IEA has done many useful things. But on supply-side modelling, where it should be in the modelling van, it has been in the baggage-train. For many years (and essentially still) the IEA's supply models simply assumed supply as sufficient, and equated this to demand. This view is not surprising as it reflects the prevailing view among most energy specialists for the last 20 years or so. But by not listening to petroleum geologists with global knowledge the IEA has misled the world with a very inaccurate picture of the energy future.

V. Group 3 Analyses, and Commentary

Group 3 analyses include those by Paul Stevens, Peter Davies, M. Adelman, Michael Lynch, and Leonardo Maugeri. The number of these analysts is relatively few, but their influence has been very great.

The reasons that these Group 3 analysts rule out the need to examine the oil resource base are various:

- Some assume that economic forces will act to prevent any supply difficulties. These economic forces include higher costs promoting exploration, bringing on smaller and less economic fields, and raising recovery factor in existing fields. This view sees these economic factors ensuring, in effect, that the conventional oil resource will be large enough that any supply difficulties are far into the future.
- Other analysts see potentially higher prices reducing demand, so bringing supply and demand painlessly back into balance.
- Some assume that an increasing supply of alternative fuels, or Kyoto-driven reductions in the demand, will ensure that the limit to conventional oil production will not be reached.
- Still others consider conventional and non-conventional oil to be economically indistinguishable, such that a resource-limit to conventional oil production will have no economic significance.

These views are discussed in part in (Bentley, 2006).

VI. Summary and Conclusions

Most Group 1 authors evaluate the size of the recoverable oil resource base by adding 2P discovery data to estimates of yet-to-find. They then use either 'mid-point' peaking (e.g., early-Hubbert, Petroconsultants '95, or Campbell-Uppsala), or specific production profiles and often, at least partly, field-by-field modelling (Miller, PFC Energy, BGR, Energyfiles) to calculate future production.

Alternative powerful techniques to predict the date of peak use linearised production based on the logistic curve (later-Hubbert, Deffeyes), or model production as an approximate mirror of discovery (Ivanhoe, Laherrère).

Group 2 forecasts assume either that large quantities of non-conventional oil will come smoothly on-stream as conventional declines (Shell; maybe Exxon), or place reliance on the USGS-2000 'total oiliness' data, paying too little attention to limits to discovery rate, production rate, and reserves growth factors outside the US (e.g., IEA-2000, US DoE, the 'WETO' study).

Group 3 analyses rule out the need to examine the oil resource base, for reasons that draw on economic and societal theory. Such analysts see no reason to examine the oil resource data quantitatively.

In conclusion, far too little attention has been paid over the last twenty or so years to evaluating the world's future global hydrocarbon supply. Early detailed calculations were largely forgotten by the energy community, and more recent forecasts from competent authorities have largely been ignored. The result is that warnings about the approaching difficulties in hydrocarbon supply are only now becoming generally recognised; very, very late in the day.

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A longer version of this paper is available from the authors.

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Table1: Results of some ‘Group 1’ calculations.

Date	Author	Hydrocarbon	Ultimate Gb	Date of global peak
1956	Hubbert	Cv. oil	1250	“about the year 2000” [at 35 Mb/d]
1969	Hubbert	Cv. oil	1350 2100	1990 [at 65 Mb/d] 2000 [at 100 Mb/d]
1972	ESSO	Pr. Cv. oil	2100	“increasingly scarce from ~ 2000.”
1972	Report: UN Confr.	Ditto.	2500	“likely peak by 2000.”
1974	SPRU, UK	Ditto.	1800-2480	no prediction
1976	UK DoE	Ditto.	n/a	“about 2000”
1977	Hubbert	Cv. oil	2000	1996 if unconstrained logistic; plateau to 2035 if production flat.
1977	Ehrlich et al.	Ditto.	1900	2000
1978	WEC / IFP	Pr. Cv. oil	1803	no prediction
1979	Shell	Ditto.	n/a	“plateau within the next 25 years.”
1979	BP	Ditto.	n/a	Peak (non-communist world): 1985
1981	World Bank	Ditto	1900	“plateau ~ turn of the century.”
1992	D. Meadows <i>et al.</i>	Ditto	1800-2500	no prediction
1995	Petroconsultants, ‘95.	Cv. oil (xN)	1800	About 2005
1996	Ivanhoe	Cv. oil	~2000	About 2010 [Prodn. mirrors Disc.]
1997	Edwards	Pr. Cv. oil	2836	2020.
1997	Laherrère	All liquids	2700	no prediction
1998	IEA: <i>WEO 1998</i>	Cv. oil	2300 ref.case	2014
1999	Magoon of the USGS	Pr. Cv. oil	~2000	Peak ~ 2010.
2000	Bartlett	Ditto.	2000 & 3000	2004 & 2019, respectively.
2002	BGR (Germany)	Cv.&Ncv. oil	Cv.: 2670	Combined peak in 2017.
2003	Deffeyes	Cv. oil*		~2005 [Hubbert linearisation.]
2003	P-R Bauquis	All liquids.	3000	Combined peak in 2020.
2003	Campbell-Uppsala	All h’carbons		Combined peak ~2015 [Includes gas infrastructure constraints.]
2003	Laherrère	All liquids	3000	See notes in text.
2003	Energyfiles Ltd.	All liquids	Cv: 2338	2016 (if 1% demand growth).
2003	Energyfiles Ltd.	All h’carbons		Combined peak ~ 2020 [Includes gas infrastructure constraints.].
2003	Bahktiari model.	Pr. Cv. oil		2006 - 7
2004	Miller, BP- own model	Cv.&Ncv. oil		2025: All poss. OPEC prodn. used.
2004	PFC Energy	Cv.&Ncv. oil		2018 - Base case.
2005	Deffeyes	Cv. oil*		2005 [Hubbert linearisation.]

Notes: Table is not complete; one notable omission is the WAES study from the late 70s / early 80s. Pr.: Probably; Cv.: Conventional; xN: ex-NGLs; +N: incl. NGLs; All liquids: Conv. and Non-conv. oil plus NGLs; All h’drocabons: Conv. and Non-conv. oil and gas. * = and probably all-oil. ‘Ultimate’: ultimately recoverable reserves (URR); is equal to the recoverable portion of the original total in-place resource. Gb: billion barrels.

Table 2: Results of some ‘Group 2’ calculations.

Date	Author	Hydrocarbon	Ultimate (Gb)	F’cast date of peak (by study end-date)	World prod. Mb/d	
					2020	2030
1998	WEC/IASA-A2	Cv. oil		No peak	90	100
2000	IEA: <i>WEO 2000</i>	Cv. oil (+N)	3345	No peak	103	-
2001	US DoE EIA	Cv. oil	3303	2016 / 2037	Various	
2002	US DoE	Ditto		No peak	109	-
2002	Shell Scenario	Cv.&Ncv. oil	~4000*	Plateau: 2025 - 2040	100	105
2003	‘WETO’ study	Ditto	4500**	No peak	102	120
2004	ExxonMobil	Ditto		No peak	114	118

Notes: *Shell’s ultimate of 4000 Gb is composed of: ~2300 Gb of conventional oil (incl. NGLs); plus ~600 Gb of ‘scope for further recovery’ (‘SFR’) oil; plus 1000 Gb of non-conventional oil. **WETO’s ultimate of 4500 Gb is for conventional oil only; it starts with a USGS figure of 2800 Gb, then grown by assuming large and rapid recovery factor gains to 2030. Mb/d: Million barrels per day.