

Oil depletion in the world

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Concern over inadequate oil supply has been in the news lately. In this article the basis for concern over future supply is discussed by analysing future production prospects using a model based on the logistic equation and past production data. The aim of the article is to make the use of the model transparent and to broadcast the result that, based on this method, peak oil production in the world is likely by the end of this decade.

Keywords: Depletion, oil, production, supply.

THE recent tripling of oil prices makes one wonder if a new oil crisis is at hand. There are many indicators to support such a conjecture and a study of the world oil situation shows that unlike the crises during the 70s, which had political origins, today's constraints to further increases in oil production appear to be based on geology. For, whereas in 1973 only one quarter of the ultimately recoverable oil had been extracted from the world's oil fields, the amount has now risen to roughly one half. To be sure, estimates of the world's recoverable oil keep increasing, but not sufficiently to balance the prodigious oil use today.

The world consumes 73 million barrels of oil each day (or in shortened form, 73 Mb/d), and if all petroleum liquids are counted, this number rises to 85 Mb/d. The difference arises largely from those liquids that are obtained as a part of natural gas production.

Consumption now takes place at the rate of one billion barrels every twelve days, but only 8 billion barrels are booked from yearly discoveries and the discovery trend is down. Furthermore, about half of the yearly consumption comes from some 120 super giant fields, most of which are over 40 years old and the 14 best producing fields account for 20% of world production¹.

That the world's oil production peak is set to arrive relatively soon was brought to the reading public in an article in 1998 by Campbell and Laherrere², both retired oil geologists. Between then and now, cheap oil has certainly vanished, and a report last year to the USA Department of Energy by Hirsch *et al.*³, warned that urgent mitigating actions were needed. Lack of action before the oil production peak is thought by these authors to have serious consequences for world economies.

The aim of this article is give an overview of the issues related to the world's oil, with the hope that the readers will gain a better understanding of the precarious energy era

which we have now entered. The deteriorating balance of payment of most oil-consuming countries is a fact today and increasingly, the war in Iraq is accepted to be one for the world's oil resources⁴, although astute observers were likely to have seen it as such even as it commenced three years ago⁵.

Geology

Oil was formed in the geological past, and a large part of its formation took place in the Cretaceous and Jurassic periods, between 90 and 150 million years ago. During that era, evidence suggests that rapid global warming led to superabundance of microbial life in the world's sedimentary basins leading to source rock rich in organic matter. By isotope analysis approximate dates for oil in any given oil province can be dated, and the earliest formations in the great inland seas push earlier prolific periods of organic sedimentary formations back into the Devonian period.

As the organic matter is buried deeper by overlying sediment, the pressure consolidates the source rock and prevents oxygen from entering the strata. Anaerobic bacteria convert the existing organic material into kerogen, which upon further burial is converted to oil.

The deep burial is a consequence of tectonic forces of the colliding plates at the continental margins and the ensuing subduction. The earth's geothermal gradient varies with formations, and its average value is 25°C for each kilometre. At a depth of between 4000 and 5000 m, temperature reaches 130–150°C, and this is sufficiently large for thermal cracking of oil to take place. This is called the oil window.

Over geological times, formation of fault lines and cracks in the crust have provided pathways for the buoyant oil to migrate, towards the earth's surface. Part of this has disappeared into nature, but some of it exists in shallow formations in which volatile components have evaporated away, leaving a heavy residue that is good for bunker fuel or bitumen. Under the best circumstances oil has found itself in a trap, with porous and permeable reservoir rock, and a tight seal. Such traps form the world's oil fields.

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The term petroleum system aims to convey the notion that all the characteristics for the occurrence of petroleum in some formation have been studied and classified. These include age of source rock, structural geology and reservoir quality.

With geochemistry known, the tools of petroleum engineering are brought to bear next to extract the oil. These include seismic surveys, three-dimensional seismic imaging, well logging, drilling technology and reservoir management⁶.

The United States Geological Survey study⁷, conducted during 1995–2000, examines the world's 159 petroleum systems and concludes that 70% of world's oil and natural gas exists in the largest fifteen petroleum systems, with the Western Siberian Basin occupying the top position owing to its large natural gas deposits. The next three, unsurprisingly, include the Mesopotamian Foredeep Basin, the Greater Ghawar Uplift of Saudi Arabia and the Zagros Fold Belt. These are followed by the Rub al Khali Basin in southeast Saudi Arabia and the Qatar Arch, Volga-Ural Basin, North Sea Grabben and Western Gulf of Mexico.

Assessment of the size of original oil endowment in the world has improved over time. As basins mature, the drilling and production history enlarges the database from which the proven reserves can be estimated. It also allows better estimation of the oil that is yet-to-be-found.

Although technology helps increase the fraction of oil that can be recovered by secondary and tertiary recovery techniques, it mainly increases the rates at which fields can be exhausted. The recovery factors depend strongly on the nature of a reservoir, and the average has increased from 22 to 35% over the last 25 years⁸. How fast a field is exhausted depends on the desired return on investment and other considerations, which may be in conflict with the optimal rate of exhaustion to yield the maximum amount of oil.

Prediction of world's peak oil production

The standard techniques to determine the original amount of oil in a petroleum system consist of plotting the cumulative recovery as a function of 'wild cats'. The colourful term, wild cats, refers to a well drilled in a new, prospective oil province and it may be a gusher or a duster. This kind of a plot is called a creaming curve and from such a curve the ultimately recovered resources can be estimated by extrapolation².

The second technique is to rank the fields in a given oil province and plot the rank versus field size. Each new discovery of a field requires rearranging of the dataset. As the dataset matures with drilling, the amount of oil in a given region can be estimated from such a plot. Since production lags discovery by certain time interval, the discovery trend is an excellent predictor of the production trend.

The curve which traces the extraction cycle for any mineral resource naturally begins from zero, rises to a global

maximum (not necessarily monotonically) and then decays toward zero. The final decay may be caused by absolute scarcity of the resource or its replacement by a better one. For example, Europe still has much non-extracted coal, as oil, natural gas and nuclear energy have replaced the previous need for coal. But, owing to excellent chemical and physical characteristics of oil as a fuel, it is difficult to see a better substitute.

By understanding the general shape of a production curve, and with adequate knowledge of discoveries, the American petroleum geologist, M. K. Hubbert, in 1956 predicted that oil production in the United States will pass its peak either in 1965 or 1971, if the ultimate recoverable oil were 150 or 200 billion barrels respectively. The peak production took place in 1970, showing that it was possible to predict the same quite far ahead of the event.

In a lengthy report in 1982, Hubbert⁹ gave a full account of the mathematical methods to predict the future production from the past production history. He based it on the logistic equation:

$$dQ/dt = aQ(1 - Q/Q_0),$$

where Q is the cumulative production, Q_0 the ultimate production, and a is a parameter showing the intrinsic growth or decay rate. Examination of this equation shows that when either Q or Q_0 is zero, the production rate dQ/dt vanishes. These correspond to the beginning and the end of oil production respectively. At the beginning, the term in parentheses on the right hand side can be replaced by unity and cumulative production is seen to grow exponentially with a as the intrinsic growth rate. Similarly, by recasting this equation in terms of $Q_r = Q_0 - Q$, it can be shown that at the end of the production cycle the cumulative production decays exponentially.

The right hand side of the logistic equation is a parabola, with a maximum at $Q_0/2$. That is, the model shows that peak production takes place when one half of the ultimate has been consumed. The parameters a and Q_0 can be estimated from the production data in the following simple way. The equation is recast as:

$$Q'/Q = a - aQ/Q_0,$$

and it gives a straight line for Q'/Q plotted against Q . Here Q' denotes the derivative dQ/dt , which is the production rate. It remains to be decided which data are to be used to fit the least squares line.

Data to estimate the parameters a and Q_0 are plotted in Figure 1, from which it is clear that there is considerable modelling error during the early part of the production history, but also that it is reasonable to draw a straight line through the data spanning the years 1983 to 2005. However, depending on which set of datapoints is used, different results are obtained, as shown in Table 1, in which the last column shows the predicted peak production year.

Table 1. Estimates for the parameters and peak production year. Units of parameter a are inverse year and ultimate production Q_0 is in billion barrels of oil

Years	a	Q_0	Peak year
1983–2005	0.050	1996	2005
1985–2005	0.049	2050	2006
1987–2005	0.048	2078	2007
1989–2005	0.048	2123	2007
1991–2005	0.045	2321	2011
1993–2005	0.043	2500	2014
1995–2005	0.043	2463	2014

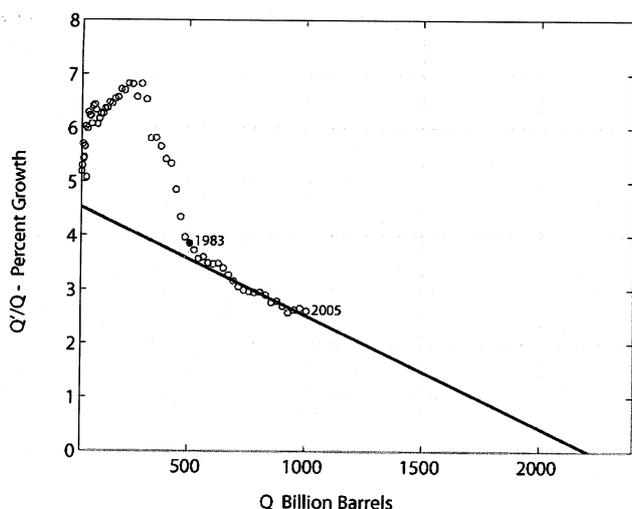


Figure 1. Parameter estimation for logistic model of world’s oil production. The least squares line is fitted through the data from 1990 to 2005.

A different calculation, which the first line of Table 1 represents, is to take 1983 as the starting year and then use the data to estimate the parameters for each year from 1993 to 2005. This causes the estimate of peak production year to move from 1999 to 2005, although not monotonically. Whereas a calculation made in 1993 puts the peak year eight years into the future, calculation carried out now gives last year as the year of peak production.

This illustrates the uncertainty in the calculation. However, the uncertainty increases the risk, for the peak production could come any time. The situation is similar to risks of inaction with regard the global warming, namely uncertainty in the calculation is a sufficient cause for delay in policies on mitigation.

Critics of Hubbert’s methodology have often pointed out that the ultimate production, when estimated this way, grows with time and the peak production year is pushed further into the future. This is a valid criticism, but one may note that for the United States peak production took place in 1970, and the peak, according to the model, has moved only to 1977 after thirty-five years of further oil production and an entirely new oil province, namely

Alaska, has been included into the mix. If only the production data for the lower 48 states are used, the year of peak production, based on the logistic model, shows insignificant drift over the years.

It is now reasonable to say that, according to Hubbert’s calculation scheme, the world’s peak production year is 2009 ± 4 years, which means that it is entirely possible that oil production in the world may begin to diminish anytime.

One can obtain further information from Hubbert’s method. Namely, at its peak yearly production rate is $Q' = aQ_0/4$. Hence the number of years, N , to exhaust the second half of the oil at the peak rate is

$$NaQ_0/4 = Q_0/2 \quad \text{or} \quad N = 2/a.$$

This calculation then shows that N is independent of the ultimate production. For $a = 0.046$, it follows that $N = 43.5$ years. If these results are used to gauge how close the peak production for the entire world is, the results are as follows: Dividing the present reserves of $R = 1100$ Gb, where Gb denotes billion barrels, with the present production of 26.2 Gb/a gives 42 years. If it is assumed that there is still 20% of oil to be found, then $R = 0.8 Q_0/2$ and the reserve to production ratio $R/P = 35$ years at the peak production. Here P , the more conventional symbol is used for Q' . Hence, this simple calculation shows that a reserve to production ratio of some 40 years should not be a cause for comfort, but for concern that the down slope of oil production is close.

Furthermore, discovery history shows that the world discovery peaked in 1964, over forty years ago, and that since year 1983, production has exceeded discovery¹⁰.

The solution of the logistic equation gives for cumulative production

$$Q = Q_0/[1 + \exp(-a(t - t_m))],$$

and the expression for the yearly production rate is

$$Q' = aQ_0/4 \cosh^2[a(t - t_m)/2].$$

The forms above have been chosen to reflect the fact that the logistic equation is autonomous. The year t_m is determined by using the cumulative production $Q_i = Q(t_i)$ at the year t_i as the initial condition.

The yearly production is plotted in Figure 2. Data for the last two years are above the theoretical estimate, which again signifies that last year may have been the peak year. With oil prices having risen from US\$ 26 in 2002 to US\$ 31 in 2003, then to US\$ 41 in 2004 and finally averaging US\$ 55 in 2005, the small rise of 550,400 barrels per day in output between 2004 and 2005 may be an indication that geological limits have been reached. Clearly, this kind of pricing environment should have provided an incentive for any country outside OPEC, which could increase pro-

duction to have done so. In fact, last year's combined production of oil for countries outside OPEC, has dropped from the previous year.

It is worth mentioning that because the logistic equation gives a symmetric production profile, critics have pronounced it useless for predicting the arc of world oil production. They further complain that there is no particular reason to suspect that the peak production should take place when half the oil has been produced, as the model has it, and that the theory does not take technological advances explicitly into account. All these objections are easy to refute.

First, the aim of the method is to predict a short-term trend in the production profile and specifically the year of peak production. No claim is made about production trend into the distant future. It is clear from Figure 2 that past production was uneven, and this already precludes symmetry, but this does not influence estimating the year of peak production. Second, the estimation of parameters, when carried out each year, shows that neither value remains fixed. Thus the ultimate production will change slightly from year to year and so will the half-way point. Clearly, the method is meant to be an approximation. Since most any curve which exhibits a peak can be approximated by a parabola, this leads to a local symmetry, which is again an approximation of the actual.

The objection that the theory ignores technological progress can be countered by noting that were it possible to quantify this progress, a space curve could be constructed with technology as the third axis. The projection of this curve, based on actual data, onto the plane of Figure 2, will thus take into account past technological advances. If there

is no reason to expect that in the future, technology will advance any more rapidly than in the past, then the space curve constructed this way will be also smooth.

Geologists know that the main hindrance to greater recovery lies in the characteristics of a reservoir. To increase production, engineers rely on various ways to reduce the viscosity and surface tension of the oil. There may be some revolutionary breakthrough, but it would have to come quite quickly to prevent the peak from taking place.

It has also been pointed out by others that the net effect of technology may also be only to increase the production rate without greater amounts of oil recovered. Hence high production would be held longer, but with steeper subsequent decline³.

There are two issues that need to be mentioned. First, the reported OPEC reserves are today 902 billion barrels of oil, whereas the world outside of the OPEC has 391 billion barrels. The latter figure includes about 175 billion barrels in the Alberta tar sands. These Canadian, non-conventional reserves need to be put into a separate category, which if done, would reduce the non-OPEC reserves even further. Since production outside the OPEC has now reached a plateau, this would suggest that the world production will reach its peak only after the OPEC's reserves have diminished substantially. Thus on this basis, the peak production year should be pushed further into the future. However, the OPEC reserves may in fact be smaller than the reported ones, as they do not show a diminishing trend no matter how much oil has been produced¹¹.

Second, oil prices have increased over the last four years, so that exploration should become more profitable. Whether the unique event of permanently high prices will bring a large number of new fields into production, will be something to watch with interest during the rest of this decade. Those projects which are now under construction are substantial, and they may, in fact, make a difference over the next few years¹². The unknown is how many more the new pricing environment brings after 2009.

Future oil supply

The world's oil production is anchored by old giant fields. These include the Ghawar field in Saudi Arabia, which is the largest oil field in the world and still produces about 4.5 Mb/d. Kuwait's Burgan field was discovered in 1938 and only this year Kuwait National Oil Company has announced that it is at the start of its terminal decline¹³. Russia's two largest fields, Somotlar and Romashkino, are also in steep decline. The former produced about 3.2 million barrels a day at its peak in 1982, providing just under one-third of the oil in the Soviet Union then. Romashkino reached its peak ten years earlier at 1.6 million barrels a day. The rate of extraction from both these fields is now less than 400,000 barrels per day, but even at these lower levels they still remain among the best fifty producing fields in the world¹⁴.

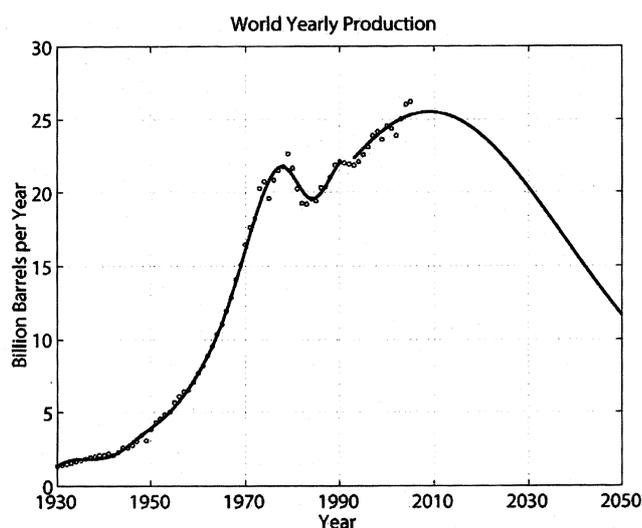


Figure 2. World oil production based on logistic equation. Model parameters used were obtained by fitting the least squares line through data spanning the years 1990 and 2005. The line up to 1990 has been drawn to aid the eye; that after 1992 is based on the logistic equation model. The actual production data are also shown. The model predicts peak production in 2009.

Production from the UK continental shelf reached its peak in 1998 and from Norway's shelf in 2000. Now the yearly drop in oil extraction from the North Sea exceeds slightly over 10% a year¹⁵. Production from the Gulf of Mexico is also in the decline, even if there is growth in oil extraction from the deep water domain. The recent hurricanes stopped production from its largest field, Mars¹⁶, and delayed the planned production from the Thunder Horse field¹⁷ until at least mid-year of 2006.

Pemex, the national oil company of Mexico announced in 2004 that oil extraction from the super-giant Cantarell complex of fields will begin to drop in 2006 at the rate of 14%. This field is the second best producing field in the world with 1.9 million barrels daily production today¹⁸.

There are still many un-drilled geological structures in Iraq, which make it the most prospective region in the world. There is little hope that much new production will begin from Iraq in the near future, which by itself also brings the world's peak production closer. Since the world uses oil at the rate of over 25 billion barrels a year, full production or its complete absence, in a country with hundred billion barrels of oil in reserves, moves the peak only two years to the future or back.

The most significant new finds are from the Caspian region and from the basins off the coasts of Angola, Equatorial Guinea and other parts of West Africa, as well as across the Atlantic from the Campos Basin in Brazil¹⁹.

Closing comments

The industrial revolution was made possible by the discovery of coal, for England's forests had been cut down by the need to find materials for sailing ships. Coal in turn was replaced by oil during the last century. This took place mainly owing to the superior energy density and transportability of oil. It is for these reasons that it has become the fuel which powers the modern industrial civilization. It also means that when oil production begins its downward trend, it will be difficult to replace it with other fuels. To be sure, there is still much natural gas left, particularly in Russia, Iran and Qatar. But its peak is also in sight.

Even coal, thought to be truly abundant, when viewed from the perspective of Hubbert's methodology, is likely to experience a declining production trend by the end of this century and thus much sooner than is commonly thought. Contributing factors include future attempts to manufac-

ture coal-derived liquids and gases, developments which will require massively increased mining operations. These would surely lead to accelerated global warming, if put into high gear.

Nuclear fuels can provide abundant energy in the future, if breeder reactors become commonplace. They pose difficulties of waste storage and possible proliferation of nuclear weapons. Still, it is doubtful that human societies will willingly give up this form of energy and be content with renewable forms, for they would severely restrict energy use. Any shift to future forms of energy sources will come with difficult adjustments, as the excellent properties of oil are difficult to match.

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Received 6 March 2006; accepted 28 August 2006