

Oil Depletion in the United States and the World

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Abstract

Oil production peaked in the United States in 1970 and the world peak is imminent. This paper gives the underlying reasons why a number of international petroleum geologists expect global crude oil production to peak soon. First, it reviews how oil was formed in the geological past and some aspects of petroleum geology. It then moves to the history of U.S. oil production and presents the methods used by M. King Hubbert to predict the U.S. oil production peak 14 years before it happened. Now the world peak is imminent. Indeed, half of world oil production comes from 120 large fields, many over 30 years old, and most are already in secondary recovery. The rate at which new oil is found has ground to a halt, with the result that world oil production is set to begin its decline sometime between the years 2005 and 2010. The implications of this decline are severe.

1 Introduction

The title of this paper suggests that oil depletion is becoming a serious issue for the United States and the world. This paper provides the basic facts and analysis to support this claim. Oil depletion is not yet in the consciousness of the general public, who only notice the rise in prices for gasoline, heating oil, and natural gas, and then are ready to pronounce a multitude of causes, few of which go the heart of the matter.

When, in the early part of the century just past, discoveries outpaced consumption by a wide margin, only a rare person worried about depletion. Even when the U.S. discovery

trend peaked in the 1930's did few take notice. New discoveries around the world were so large that there was little concern even in 1947 when the United States began importing oil, as its own oil industry could no longer keep up with rising demand. Finally in 1970 oil production in the United States peaked, but even this went unnoticed [1]. It took the oil embargo of 1973 to alert the public and their leaders that oil resources are limited and it was time to move to smaller cars, insulate houses better, and begin other conservation efforts.

These efforts were short lived. Although oil price spiked when the Shah of Iran fell in 1979 and also in the beginning of the Iran-Iraq war which lasted from 1980 to 1988, a drilling boom outside the Persian Gulf brought new supplies of oil. North Sea production was increasing and the giant Prudhoe Bay field in Alaska fed the oil appetite of the United States. The new found supplies held prices in check through the 1980's. Despite another price spike caused by the Gulf War in 1991, in late 1998 oil price had dropped to near \$10 per barrel and the respected English magazine Economist ran a cover story, *Drowning in Oil*, that suggested that it might head to \$5. This extraordinarily low price led OPEC, together with Mexico and Norway, to cut production and a year later oil soared back to \$36. High oil prices have historically lead to recessions and this time the conditions for it were aided by an unsustainable stock market bubble. Anticipating slower growth in the world economy, traders in the mercantile exchanges drove the price of oil down to \$17 per barrel. A new round of cuts by OPEC and international tension has brought the price back to \$25, where it stands today as the turmoil in the Middle East is growing by the day. The latest news in the press focus on the increases in Russian oil production and how it, rather than OPEC, will assume the prominent place in oil exports. How this unfolds is for all to watch during the next year or two.

To understand oil depletion one needs to stand back from the confusion of mixed signals that appear in daily papers and TV, whether proffered by journalists or by oil industry spokesmen. The former are generally ill-informed and the latter, by virtue of their position, prone to give a one-sided account. For an informed view one needs to search for an independent analysis. Such an analysis appeared in the March 1998 issue of the *Scientific American* under the title *End of Cheap Oil*. Its authors, Colin Campbell and Jean Laherrère [2], are both retired international petroleum geologists, each with over 40 years of experience working, in the case of Colin Campbell at Texaco, BP, and Amoco, and for Jean Laherrère at the French oil company Total. Their article points to a peak in oil production by the end of this decade and probably sooner. The cause is depletion in the various oil provinces of the world and hence the condition of diminished supplies will be permanent.

Everyone seems to agree that sometime in the future oil will be exhausted, but the perception is that the day is still far away. This view arises from the common pronouncement that *at present rate of production the discovered reserves will last 40 years*. Although this is true, it is highly misleading, for it presents a picture in which production is flat for 40 years and then drops to zero after that. The likely scenario is that oil production increases until depletion overtakes production and then production drops at some specified yearly rate until it is exhausted. When the world enters this downslope, half of the original oil endowment will still be there to be extracted. This is cold comfort for the consuming countries who are faced with a struggle to get by with diminished supplies each year.

To help understand the predicament humanity is forced to face in just a short time, this

paper is organized as follows: The first section is a brief overview of the origin of oil, how it is formed, and where it is found. Petroleum geologists today have a firm grasp of these issues and they also know which regions of the world are non-prospective. Next, the history of oil production in the United States is discussed and methods developed by M. King Hubbert are used to show how future oil production can be predicted. The Hubbert model for oil production provides a basis for the imminent peak in world oil production and the paper concludes with a personal view of how our common future may evolve.

2 Origin of Oil

This section is a short introduction to petroleum geology, starting with a discussion of sedimentary basins, reservoir descriptions, and the movement of tectonic plates in the geological past. Geology provides an explanation of where oil is likely to be found and in which parts of the globe there is none.

2.1 Sedimentary Basins

Oil originates in the sedimentary basins of the world. Particularly important are those basins that have been on the continental shelves for millions of years. Rivers that emptied into them brought effluents composed of silt and remnants of vegetation. In the nutrient rich surface waters of such basins and with the energy of the sun, a profusion of microbial life thrived during *certain particular epochs* of the geological past. At the end of their short life-cycle these micro-organisms sank to the bottom and there together with other sediment formed layers of carbon-rich organic matter.

Although the continental margins are the most important basins, other large inland bodies of water have also provided a setting for the same life-cycle. The Caspian Sea is an example that today receives a great deal of attention.

When the early sediment layers at the bottom of the basin were covered with later sediment, the deeper layers were deprived of oxygen and the organic matter in them did not decay, as it does in the common setting of a kitchen compost. Anaerobic bacteria, however, go to work and turn the organic matter into the substance *kerogen*. Kerogen can be thought of as immature oil. To understand its fate requires a short detour to earth science [3].

2.2 Oil Reservoirs

The earth's oceanic crust is about 5 miles thick and the continental crust varies in thickness from between 25 and 37 miles. The crust is broken into *crustal plates* below which is a hot molten *mantle*. This means that temperature increases with depth with a global average rate of 74 degrees Fahrenheit per mile. At the depth from 6000 ft to 13,000 ft temperature and pressure are right for kerogen in the *source rock* to be cracked into oil. This zone is called the *oil window*. At depths greater than 13,000 ft temperatures are so high that oil is cracked into gas [4].

Convection currents in the mantle cause the crustal plates to drift slowly. As they drift, boundaries of the plates collide and on one side *folded mountains* are formed. On the other side a plate sinks deeper into the earth. In this way, the rock formed in the sedimentary basins *may* be brought into the oil window and the kerogen in the rock can be converted to oil. At this depth the overburden bears down on the source rock and creates a high pressure. Thermal cracking of kerogen to oil increases the pressure further and to relieve the pressure, oil will migrate to surrounding strata if a path is open for it. All this takes place slowly over a time spanning millions of years. Thus, there has been ample time for the shifting strata of the crust to create an opportunity for oil to migrate. In fact, much of oil that was created over time must have reached the earth's surface and disappeared into nature. The earliest oil fields were found where there was visible evidence that such a seepage has taken place [4].

The strata under a range of folded mountains tend to have a shape similar to the mountain itself. Such a feature can be pictured as a domed hallway, with the technical term *anticline*. If an anticline consists of *porous and permeable rock* and is covered by an impermeable *seal*, preconditions for an oil field are in place. Oil fields tend to be found not under the mountains, but in the foothills and valleys between the mountain chains.

To hold the oil in a *trap*, the seal must be of impermeable rock. One such rock is gypsum, formed by evaporation of sea water. It is a dihydrate of calcium sulfate. As gypsum is buried deeper, it loses its water molecules and acquires the name *anhydrite*. Such anhydrite layers are excellent seals.

The rock which holds the oil in its pores is called *reservoir rock*. If it is also permeable, which means that the pores are connected, oil can flow through it. The reservoir rocks in North America tend to be sandstones and those in the Middle East dolomite. *Most* of world's oil has been found in these anticlinal traps, and no advanced seismic technology was needed to find it [1].

2.3 Plate Tectonics

The theory of plate tectonics explains why continents move. Developed in the 1960's it has led to a view that today's continents formed from one super-continent about 250 million years ago.

The general motion of the tectonic drift has been in a north-easterly direction. As a consequence, oil is found mainly in the northern hemisphere. As the continents separated, sedimentary basins formed between the separating continents. Two basins that figure prominently in oil production are the Persian Gulf and the Gulf of Mexico. The newest oil provinces are the deepwater regions off the coast of Brazil and West-Africa, in the waters of Nigeria, Equatorial Guinea, and Angola. They are ancient sedimentary basins between South America and Africa [4].

2.4 Preconditions for Oil to Form

The knowledge gained from oil exploration has been organized and today the term *petroleum system* is used to describe the various aspects of the dynamical setting in which oil is present in some region of the world. This includes how the oil was formed, when it was formed,

the structural geology of the region, and other relevant information to characterise it fully. The United States Geological Survey, USGS, in its latest comprehensive study two years ago analysed 159 such petroleum systems in the world [5]. This study gives petroleum geologists a comprehensive view of the world's oil and natural gas reserves, where they are, how much there are, and which parts of the world are barren of oil. It also gives them a document against which to compare their own knowledge and to offer differing judgements on the potential for future increases in oil supply.

In summary, oil is found in select regions of the world and a number of conditions must be met for oil to form and be trapped. Namely, the source rock must have migrated in the geological past into the oil window and remained there long enough for kerogen to have been cracked into oil. Oil, during its migration toward the earth's surface, must have been blocked by a sealed trap and collected in reservoir rock which is both porous and permeable. That these conditions are often not all met simultaneously accounts for the large number of dry wells that oil companies drill around the globe. Furthermore there are many regions of the world that for geological reasons are non-prospective. Random drilling will not find new oil.

3 U.S. Oil Production and Reserves

This section begins with some definitions of what *reserves* mean and what goes into the yearly production numbers of oil. History of U.S. oil production is discussed next. It is followed by an introduction to methods used to predict oil production rates and their application to the U.S. experience. The section concludes with a discussion of the future oil prospects for the United States.

3.1 Proven Reserves and Liquids

The initial estimate of oil in a field is called a *scout* estimate, given by a company with this speciality, or by the company holding the concession. It consists of an estimate of oil-in-place and recoverable oil. This information is a company secret and from it a number can be assigned to *reserves*.

More complete seismic surveys modify the initial estimate and confidence in its value increases after exploratory drilling has been carried out. As a field goes into production its ultimate yield finally emerges from the rate at which its production declines. When the field is abandoned part of the oil-in-place is still left, but this part is no longer counted as reserves.

The size of the reserve is called either *proven*, or *proven and probable*, or still *proven, probable and possible*, depending on the certainty of the estimate. Proven reserves are those which have ninety five percent chance of being produced and are therefore at the lower end of the estimated reserves. The larger estimate for proven and probable is owing to it being assigned a fifty-fifty chance of being produced. For proven, probable and possible, this drops to five percent.

The rules imposed by the Securities and Exchange Commission, SEC, in the United States requires that only proven reserves are reported. Hence, as companies develop their fields and thereby obtain a better assessment of how much of the oil-in-place can be extracted, part

of what were *proven and probable* reserves, become *proven* and this part is then reported to SEC and published. This accounts for *reserve growth*. It also underscores how lack of uniformity among various countries makes the task of determining what reserves to count quite difficult.

Hope that new technology will also increase reserves is largely an illusion as the main effect is to deplete the field faster. How much of oil can be recovered depends on the reservoir characteristics, particularly the permeability of the reservoir rock. Carbon dioxide injection changes the viscosity of oil, which makes the oil flow more readily. But only if an effective way could be found to decrease the surface tension between oil and rock, would the recovery increase substantially. Many years of efforts in these *tertiary recovery methods* have not made much difference.

Secondary recovery techniques depend on pressurising the reservoir to force the extra oil out which would not flow under its own pressure. These are routinely used to produce oil at a rate faster than would be possible when oil flows without the extra effort.

There is a further cause of confusion which stems from what to count as oil. Some of the hydrocarbons at high pressure in reservoirs are in gaseous state. When the hydrocarbons flow from a well, their pressure is released and some of the gases condense. This part is called *lease condensate*. In addition, the heavier hydrocarbons from natural gas production are in liquid form. These *natural gas liquids*, NGL, may also be added to the oil stream. When these and all other liquids such as *refinery gains* and *synthetic liquids* are combined *total liquids production* is reported. For the world oil production in 2000 was 68.2 million barrels per day and 76.7 million barrels per day for all liquids.

3.2 History and M. King Hubbert

The oil industry in the United States began in 1859 when oil was discovered in Titusville, Pennsylvania. From there the industry moved to Texas after the dramatic spudding of the Spindletop well near Beaumont in 1901. Oil's early use as lamp oil and for lubrication was superceded by refining it for use as gasoline in automobiles, with Henry Ford's Model-T paving the way in 1909.

During the years 1901-1930 George Otis Smith was the head of the United States Geological Survey and in 1918 he warned that U.S. production was set to decline in 2 to 5 years and that all the oil in the world would be exhausted by 1940. His was not the only prediction of scarcity ahead, but deserves special mention owing to his important position. Those who have an optimistic disposition to oil depletion collect such predictions to show how often and how badly the pessimists have have been wrong [6]. Such rhetorical tricks rest on weak logical foundations and cloud discussions of the fundamental issues.

New oil fields were discovered throughout the great depression, with the East Texas field discovered in 1930. It remains the largest field ever discovered in the lower-48 states. Today we know that decade of the 1930's marked the peak discovery in the United States.

During this early period the most far reaching studies of U.S. oil reserves and future production were carried out by M. King Hubbert, born in 1903 in Texas. He began his higher education in 1921 in a Texas junior college and then moved to the University of Chicago, from where he graduated in 1926. He took his M.S. there in 1928 and began a

PhD study, but it was interrupted when he was asked to join Columbia University to teach geophysics in 1930. He remained at Columbia as an instructor until 1940 and during this period submitted his doctoral dissertation to the University of Chicago in 1937.

In 1943 Hubbert joined Shell Oil Company's research laboratory and later was its director. While there he made important contributions to the understanding of petroleum geology and other aspects of oil production and its depletion. These contributions led to his prediction in 1956 that oil production in the U.S. lower-48 states would peak in the early 70's [1]. As many had been proved wrong before, this was a bold prediction, but it turned out to be right. His analysis was based on a U.S. oil endowment of 170 billion barrels (Gb).¹

3.3 Hubbert's Peak

The mathematical basis for the prediction of peak production comes from the work of Verhulst in 1838 on human population growth [7] and Hubbert employed it in his later work. Laherrère discusses the uses of Hubbert's methods; under what conditions they are appropriate to use and when they are not [8]. Deffeyes, in a recent book to a general reader, gives an account of these methods and the description below follows his treatment [1].

To analyze oil production, let Q denote the *cumulative* amount of oil that has been produced from the beginning of oil industry to present. Verhulst equation, also known as the logistic equation, states that the rate of increase of the cumulative production, which can be taken to be the *annual production*, is given by

$$\frac{dQ}{dt} = aQ\left(1 - \frac{Q}{Q_0}\right)$$

in which a represents the *initial growth rate* and Q_0 is the *ultimate production*. This is to say, the amount of oil that has been produced when a region is completely depleted. The right hand side is seen to be a parabola which increases from zero at $Q = 0$ to a maximum, then drops to zero again at $Q = Q_0$. Its maximum value is $aQ_0/4$ at the *midpoint of ultimate production*.

The solution of this equation is

$$Q = \frac{Q_0}{1 + e^{-a(t-t_m)}}$$

where t_m is the year of peak production, at which time $Q = \frac{1}{2}Q_0$. The rate of production can now be shown to be

$$\frac{dQ}{dt} = \frac{aQ_0}{4 \cosh^2(\frac{1}{2}a(t - t_m))}$$

For a hypothetical country in which the ultimate production is $Q_0 = 240$ Gb and the peak year is $t_m = 1970$ results are shown in Figure 1. The data for this country happens to be close to those for the United States. Included in the graphs shown in Figure 1 are hypothetical annual production data that have been chosen such that they agree with the theory.

¹Gb, Mb, and kb are used to denote giga, mega and kilo barrels of oil, with giga for billion, mega for million and kilo for thousand barrels. Gb/a and Mb/d are used for billion barrels per annum and million barrels per day.

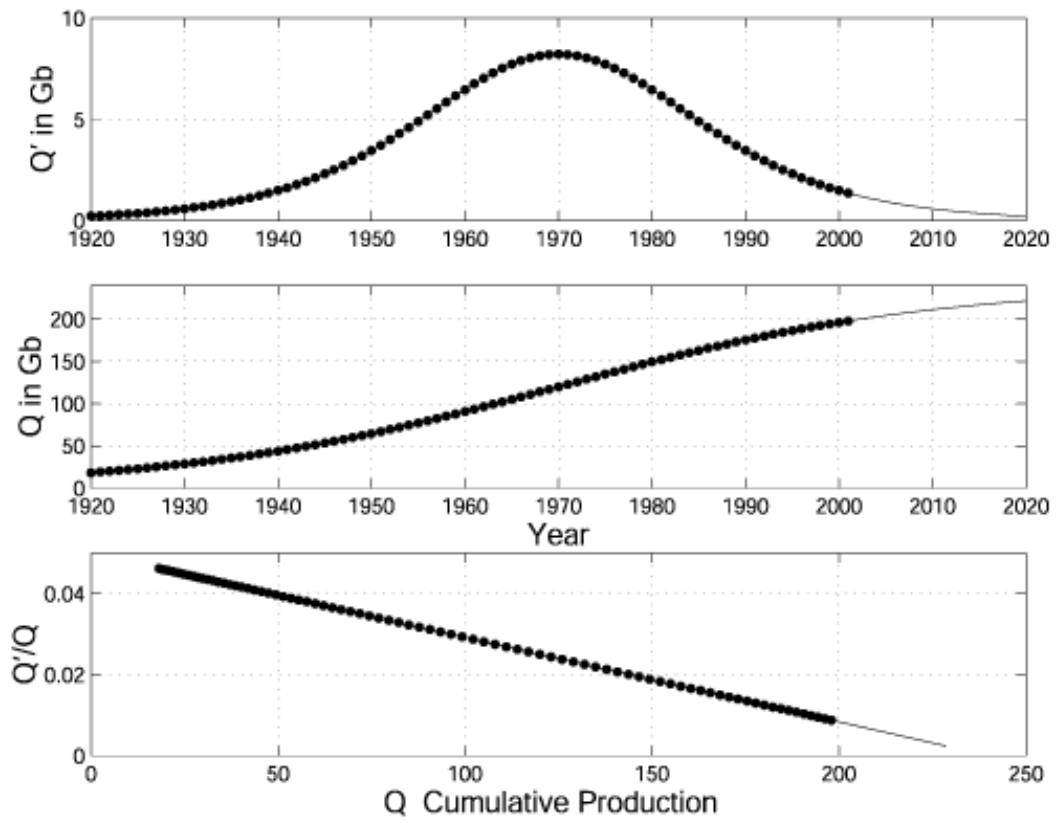


Figure 1: Theoretical Hubbert Curves for a Country with Oil Endowment of 240 Gb and a Peak in 1970.

The top graph gives the annual production. It is symmetric about the peak. In the middle graph the cumulative production is seen to be S-shaped, with an *inflection point* at peak production and an *asymptote* at 240 Gb, somewhere in the future.

If the logistic equation is arranged as

$$\frac{1}{Q} \frac{dQ}{dt} = a - \frac{a}{Q_0} Q$$

then it is seen to represent a straight line in coordinates with Q along the horizontal axis and Q'/Q along the vertical, where $Q' = dQ/dt$ represents the time derivative of Q . The slope of this line is negative and has the value a/Q_0 . It intersects the vertical axis at a and the horizontal one at Q_0 . Hence from this plot estimates can be made for both a and Q_0 from the actual production history. The hypothetical data are plotted this way in the bottom graph of Figure 1.

3.4 U.S. Production Curves

The data to determine the U.S. production are available from the Energy Information Administration, EIA, web-site [9]. This organization is a branch of the United States Department of Energy. Since the data series begins at year 1930, an estimate for the cumulative production prior to this is needed. Campbell [4] gives 11.84 Gb for it. The actual data plotted in Figure 2 in the manner just discussed gives an initial growth rate $a = 0.054$ and an ultimate $Q_0 = 233$ Gb. These were obtained by fitting a least squares line through the last twelve years of data. The data does not justify this high degree of accuracy, hence a slightly larger value 240 Gb will be used for the U.S. ultimate. This is in contrast to official estimate of 362 Gb from the USGS report and it raises serious questions on the methodology by which this substantially larger number is obtained [1].

The cumulative production can now be plotted. It is shown in Figure 3, with the estimates by EIA for this year and the next. The amount produced in the United States at the end of 2001 is 184 Gb. Since the published reserves are 22 Gb, this leaves 34 Gb to a category that includes, what USGS calls *reserve growth* of existing fields and *yet-to-find*.

The annual production is given in Figure 4. It shows the oil peak in 1970. The subsequent decline and rise in production were a result of conservation efforts and a drilling boom in the Gulf of Mexico. Contributing factor for the secondary peak was also the completion of the Alaska pipeline. Deepwater oil production in the Gulf of Mexico may slow the rate of U.S. depletion for the next few years, but once production in the deepwater Gulf of Mexico starts declining, the decline rate will accelerate.

The key to Hubbert's prediction was his recognition that *oil production must follow its discovery pattern*. By studying the discoveries, which peaked during the 1930's, he could make his bold prediction. Although it was dismissed, it turned out to be quite accurate. Many will also dismiss today the prediction of the imminent world peak, even if the predicted peak is closer and data firmer than in 1956 when Hubbert carried out his study.

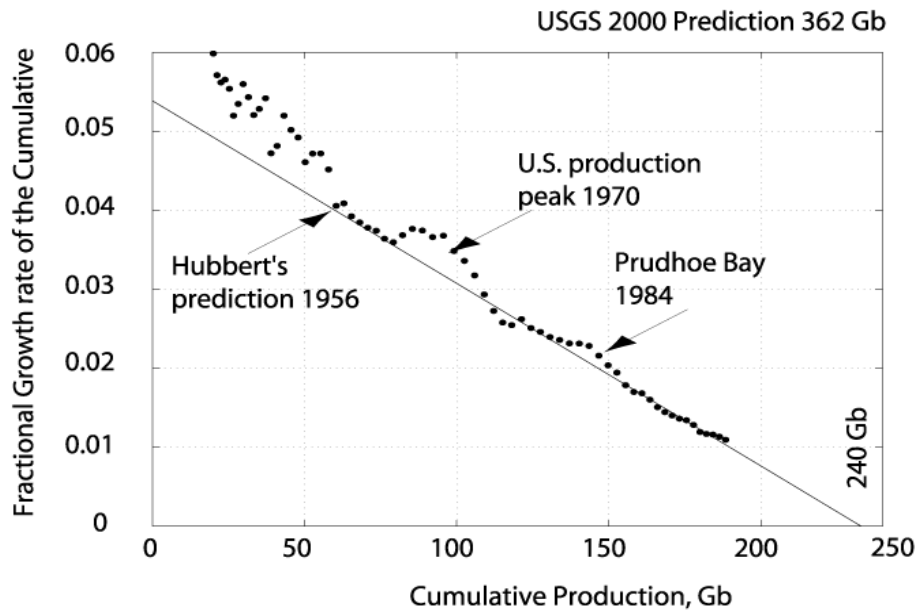


Figure 2: Estimation of the United States ultimate production.

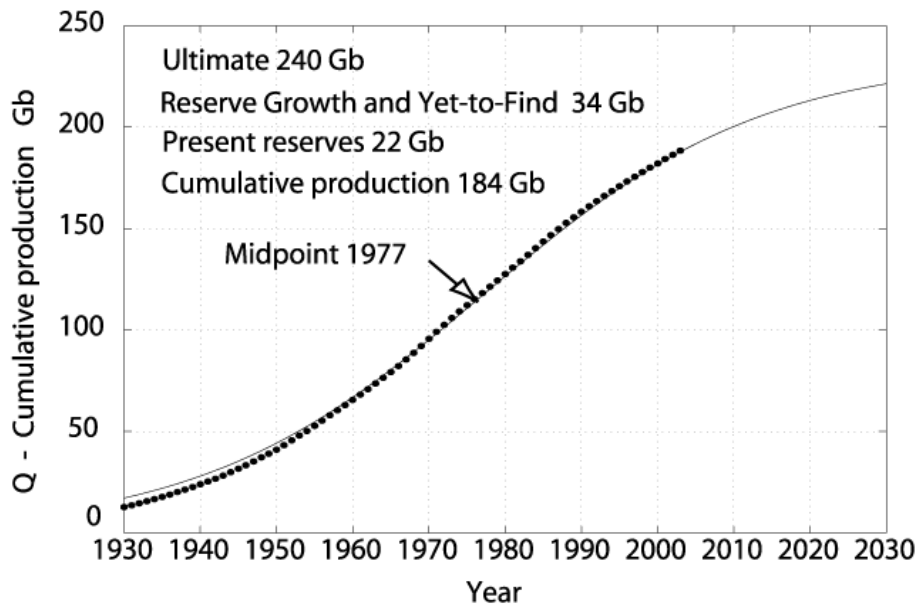


Figure 3: Cumulative United States production with ultimate 240 Gb, published reserves 22 Gb, leaving 34 Gb for reserve growth and yet-to-find.

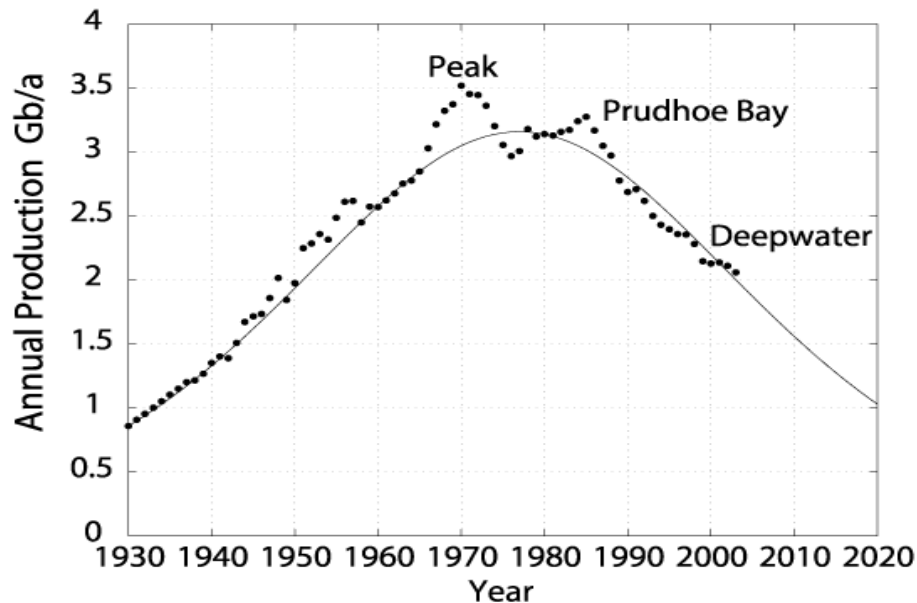


Figure 4: Annual United States production with a theoretical peak at 1977 although the actual peak was in 1970. Alaska’s oil production caused the secondary peak.

3.5 Alaska and Deepwater Oil

The Prudhoe Bay field in Alaska, which is the largest field ever found in North America and the fifteenth largest in the world, was discovered in 1965. It began producing oil in 1977 and achieved its highest production 1988. Estimates for its ultimate reserves have ranged from 9 to 13 Gb, but as Figure 5 shows, it is likely to have had nearly 12 Gb of oil. At its peak it produced 1.56 Mb/d and still delivers about 500 kb/d. The Kuparuk River field produces 200 kb/d and is the second largest field in Alaska. The newest fields are the Alpine (2000) and North Star (2001) fields and are producing about 100 kb/d each. Other fields are smaller, but all together Alaskan production today provides 1.0 Mb of the 19.7 Mb used in the U.S. daily [10].

Current controversy is centred on oil in the Arctic Wildlife Refuge, ANWR. Seismic surveys put its ultimate at 5 to 8 Gb range, but more reliable estimates will only become available after exploratory drilling commences. Even at the low end of this estimate this will be a sizeable amount oil and when it is developed, its peak production is estimated to be 400 kb/d. At that time its production will be larger than from any other field in the United States. That it will be drilled one day is a foregone conclusion, for when shortages appear every argument against drilling it will be dismissed by the public’s clamour for oil. Today the discussion on both sides is largely colored by political considerations. The most appealing argument is to save it as long as possible, for once all efforts have been made to shift into a thrifty living, any oil from it would go further. The facts are, however, that Alaska just like the rest of the country, is in decline.

Water depths at which off-shore drilling operations have been carried out have been

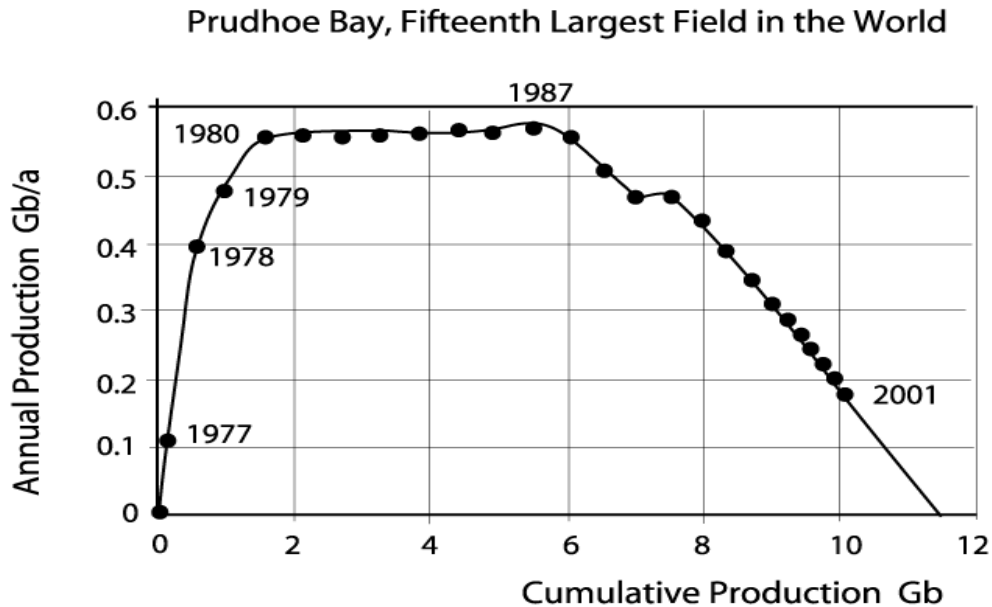


Figure 5: Production history of Prudhoe Bay field.

constantly increasing. It used to be that the dividing line between shallow and deepwater drilling was the water depth of the continental shelf, which is about 700 ft. As technology developed, drilling at greater depths than this became routine. Today the boundary is at 2000 ft. Anything beyond this is considered to be ultra-deepwater, but it appears that this demarcation may also shift. Whereas only ten years ago the deepest drilling operations were at 3300 ft, a new record of 9700 ft was set last year in the Gulf of Mexico, where oil was found at approximately 20,500 feet of total depth [11]. This puts the oil 10,800 ft below the sea floor and into the oil window. Thus it appears that it has not migrated to any shallower reservoirs. In the beginning of the Gulf of Mexico development it was thought that its hydrocarbons were mostly natural gas rather than oil. This view has changed and according to Nehring the lower geothermal gradient there is not sufficient to crack the oil to gas [12]. Consequently, the deepwater Gulf of Mexico is the most promising oil province in the United States and it is likely to slow the depletion rate of the U.S. for perhaps next six years. There are three fields in the deepwater Gulf of Mexico that produce over 100 kb/d of oil.

The federal waters off the California coast are off-limits to exploration. Considering that there are three fields in California that deliver over 100 kb/d of oil, it is likely that California coast is a prospective oil province. The eastern part of Gulf of Mexico is also closed to exploration. These, together with ANWR are the last areas in which substantial amounts of new oil can be found in the United States [13].

3.6 Imported Oil

United States consumes 19.7 million barrels of oil daily. It imports 58 percent of this, a fraction that will continue to increase as U.S. fields deplete. Over half of the imported oil comes from Canada, Saudi Arabia, Venezuela, and Mexico. A comment heard often is that the United States is less dependent on Middle Eastern oil today than it was 30 years ago. Since oil is fungible, meaning that it is traded on a world market, the country of origin makes no difference, as transportation costs determine the destination. When oil becomes scarce, those willing and able to pay, will secure the oil without regard from where it comes.

4 World Oil Reserves and Production

In this section *world oil* reserves and production are discussed, and the main producers identified. Their potential for future production is then presented. The section concludes with a discussion of the world peak.

4.1 Estimates of World's Oil Endowment

Hubbert made two estimates of when the world oil production will peak. For the world he assumed an endowment of either 1350 Gb or 2100 Gb. The latter gave a peak around the year 2000. To estimate the peak production, Hubbert needed a good estimate of the ultimate oil endowment. Studies completed in the 1940's had concluded that this number was less than 1000 Gb. However, already in the 1950's estimates of the world endowment had increased to about 2000 Gb. They have changed little since then. In fact, 64 studies carried out since 1950 gives this as an average value. From this estimate and using the value $a = 0.054$ obtained from the U.S. data as a guide, the *maximum daily production for the world*, using the formula $Q' = aQ_0/4$ derived above, comes to 74.0 Mb/d, which is *very close* to the production of 68.2 Mb/d for oil and 76.7 Mb/d for all liquids for the year 2000. This determination could have been made at least thirty years ago and was made by Hubbert nearly fifty years ago. *This is quite striking.* Indeed, in a critical examination of past predictions Bentley [14] points out that those carried out in the 1970's and which were sponsored either by large oil companies, such as Esso and Shell; by governments such as U.K. Department of Energy and the U.S. Congress; or by institutions such as the World Bank, all show that world oil production would peak around year 2000. It appears that world leaders and population at large have ignored this fact during the last quarter century.

A method to estimate the ultimate endowment of any region of the world is to plot the amount of oil discovered as a function of the number of *new field wildcats* drilled. This is called a *creaming curve* and it discussed by Campbell and Laherrère in their Scientific American article. By this method Laherrère comes up with the following estimates [15]:

Region	Gb
Middle East	820
Latin America	270
US and Canada	250
Africa	220
Former Soviet Union	215
Asia	145
Europe	115
World	2000

Table I. Estimated Ultimate Reserves in Various Regions of the World.

This table supports the 2000 Gb number for the world and gives the break down by regions. Laherrère has taken a very critical stand against published data that suggest a much higher estimated ultimate recovery value and considers them highly misleading. These data are discussed in the next section.

4.2 Country Statistics

The world's oil reserves and production statistics are given annually in two industry magazines, Oil & Gas Journal and World Oil. Neither journal carries out an independent analysis of proven and possible reserves and publishes the figures submitted by the 98 countries that are listed. Discrepancies between the published data and technical field data are common. However, the world relies on the accuracy of the submitted data, even if they may be unreliable. British Petroleum Statistical Review of World Energy [16] is a yearly summary of energy production and its consumption. For oil production it lists 48 countries.

From the 2001 BP-report oil reserves for the twenty largest producers, accounting for 84% of the production are given in Table II. Included are also reserve data from the 2001 year-end issue of the Oil & Gas Journal and the March 2002 production figures. The capacity estimates come from Ismail, an analyst for OPEC office in Vienna, and from *Oil Market Intelligence* [17]. The top part of this table lists the eleven OPEC members, the lower part the major producers outside OPEC.

There are over 4000 producing oilfields in the world. Simmons [13], in a report *The World's Giant Oil Fields*, lists the top 120 that account for 47 % of the world's oil. The bottom half account for 12% of the world output, the top nineteen produce over 22 % of the world's daily consumption, and those discovered during the last decade about 2%. Over 70% of world's oil comes from fields discovered before 1970. Many are in secondary recovery. The decline of the Prudhoe field is shown in Figure 5. Thus consider a situation when most of the old fields enter their decline stage. It is not hard to imagine what happens then. The frenetic rush to bring new supplies by bringing smaller fields into production will not replace the decline in these aging fields and the world is faced with a permanent scarcity.

The country summaries that follow rely on data from the latest BP Statistical Review of World Energy and on Simmons's study of the state of the old fields in the world. It also makes use of Campbell's extensive studies [4] and the comprehensive paper by Laherrère [15]. Bakhtiari [18], the senior analyst of the National Iran Oil Co., is an insider and thus has the most intimate knowledge of the Middle Eastern fields. He questions whether OPEC can meet the projected oil demand during the next twenty years. This would be needed to compensate for the decline in oil production outside the Persian Gulf by 8 Gb/a during this period.

SAUDI ARABIA has the largest reserves and production in the world. Its Ghawar field is by far the world's largest oil field with an estimated 70 Gb for its ultimate and is believed to account for 50% of Saudi production. Its Safaniya field with 30 Gb as its ultimate is the largest off-shore field in the world. It produced at one time over 1 Mb/d, but now produces half of this. Seven fields in Saudi Arabia make up over 85% of its production. Saudi Arabia is engaged in an aggressive drilling program to keep the Ghawar field producing at its current rate. This suggests that it has entered its secondary recovery stage.

IRAN is a very old oil province, where a trickle from Chiah Surkh in 1904 turned into a torrent from Masjid-i-Suleiman in 1908 [19]. Its peak production of 6 million barrels per day took place in 1974. During the Iran-Iraq war its oil industry was partly destroyed, but has recovered since. Old fields, which are all in secondary recovery, account for 85% of Iran's oil production. Six of them at one time produced over a million barrels each, but now they collectively have a daily production of just over million barrels. There are new off-shore fields under development.

VENEZUELA is also an old oil province. Its four oldest fields produced at one time together over 2 million barrels a day, but this has dropped to 850,000 barrels. It struggles to keep its production up. Daily news from Venezuela indicate severe political difficulties for the country, the unhappiness often expressed by strikes by oil industry workers.

IRAQ's oil production comes mainly from two large fields. Kirkuk, discovered in 1927 and which thirty years ago was the second largest producing field in the world. In 1990 its reserves were estimated to be 10 Gb and production 1 Mb/d. Today it produces 900,000 b/d. Iraq's second largest field is Rumaila, near the Kuwait border. Discovered in 1953, in 1990 it had 11 Gb left. It produces 1.2 Mb/d. These two fields account for 78% of Iraq's production. It has the most oil production potential in the world, with three 10 Gb fields found since 1975, but of these only the West Qurna field is under production. Owing to the UN sanctions Iraq is likely to be the last major producer to reach its peak production.

NIGERIA's oil comes from a large set of small fields. Its oil production peaked in 1978, declined in the 80's, but has made a robust recovery during the last ten years. It is unlikely to grow production from here.

UNITED ARAB EMIRATES has Abu Dhabi and Dubai as its two main producers, the former accounting for 85% of its production. It has 13 producing fields, but over 60% of its production comes from just three fields. Its peak production is still in the future, probably in 2008. Dubai's two large fields account for most of its production. Both are in secondary recovery and the emirate is past its peak production.

KUWAIT's Burgan field is the second largest in the world. It was discovered in 1938 and still produces most of Kuwait's oil. Of the seven other producing fields in Kuwait, two produce more than 100,000 barrels per day.

LIBYA's eight largest fields produce 70% of its total. Most of its fields were discovered 40 years ago. It is past its peak production.

ALGERIA's largest field Hassi Meassaoud was discovered in 1956 and it accounts for nearly 40% of this country's production. Algeria is past its peak.

INDONESIA's population of 150 million makes it one of the most populous countries in the world. It uses 70% of its oil production for domestic use. Its fields are old and it is past its peak production.

QATAR is a large producer of natural gas. Natural gas liquids and condensate add to its liquid production, as 80 % of its oil comes from a 60-year old field.

RUSSIA's oil industry went into a downturn during the collapse of the Soviet Union. It has recovered since and now competes with Saudi Arabia for the position of the world's top producer. According to Laherrère its ultimate reserves are about 170 Gb, hence much larger than those tabulated by Oil & Gas Journal. Still, they do not compare to Saudi ultimate reserves and the battle for oil production leadership will be short lived. Many of its fields are old and they deteriorated during the 1990's. For example, its Samotlor field, discovered in 1965 with an original endowment of 20 Gb, produced at the rate of 3.5 Mb/d in the early 80's, but now production is down to 300,000 b/d.

CHINA imports more oil than it produces. China's Daqing field was discovered in 1959 and is still the fourth largest producing field of the world with over million barrels a day. Shengli field is the second largest field in China, but it is much smaller than Danqing as it produces about 500,000 b/d. The third largest field in China is Liaohe which produces 280,000 b/d. These three large fields in China are now in the decline phase. Owing to its rapid industrialisation, China's oil consumption is increasing rapidly.

NORWAY is the second largest oil producer outside OPEC after Russia, as its own needs are small. It is entering its peak production year. Laherrère from his studies of reserve growth puts its ultimate reserves at double the figure published in Oil & Gas Journal and World Oil. Still, its production will decline swiftly in coming years, although not as fast as that of U.K.

MEXICO is one of the main exporters of oil to the United States. Its Cantarell field was discovered in 1976 and it produces over a million barrels per day. It is the third largest producing field in the world. A large gas injection to keep its production intact has been underway. Since the government of Mexico relies heavily on oil revenue, only a small part of the cash flow from oil production goes to new investment. Mexico's production will begin to falter if its investment is reduced. It still has unexplored territory in the Gulf of Mexico.

CANADA is past its peak production in conventional oil, but its production of non-conventional oil will grow. Its new oil province for conventional oil is offshore from Nova Scotia.

UNITED KINGDOM achieved its peak production in 1999. By properly handling the reserve additions Laherrère estimates its reserves to be 15 Gb rather than the 5.0 Gb reported in BP Statistical Review of World Energy [16]. This large discrepancy will diminish with reserve growth.

BRAZIL has found new deepwater fields off its northeastern coast and is still increasing production even though its reserves are small. Its Marlin field produces over 500,000 b/d.

OMAN is on the Persian Gulf but not a member of OPEC. It is likely to peak soon owing to its low reserves.

Country	Production	Capacity	OGJ Res.	BP Res.
	kb/d	kb/d	Gb	Gb
Saudi Arabia	7330	9800	259.3	261.7
Iran	3370	4050	89.7	89.7
Venezuela	2597	3000	77.7	76.9
Iraq	2567	3100	112.5	112.5
Nigeria	1992	2400	24.0	22.5
United Arab Emirates	1955	2450	97.8	97.8
Kuwait	1844	2400	94.0	96.5
Libya	1295	1450	29.5	29.5
Algeria	796	880	9.2	9.2
Indonesia	1160	1275	5.0	5.0
Qatar	605	750	15.2	13.2
Total	25511	31555	813.9	814.5 78%
Russia	6416		48.6	48.6
Mexico	3012		26.9	28.3
United States	5822		22.0	29.7
China	3237		24.0	24.0
Norway	3213		9.4	9.4
Brazil	1128		8.5	8.1
Oman	933		5.5	5.5
Canada	1392		4.9	6.4
United Kingdom	2436		4.9	5.0
Total	27589		154.7	165.0 15%

Table II. World's Main producers of oil

4.3 Spurious Reserve Additions

Campbell and Laherrère point out in their Scientific American article how the oil reserves in the Persian Gulf region took a sharp increase in the 1980's. They attribute these increases to quota battles in which each country's production quota became tied to their reserves. As a consequence each OPEC country increased its reserves and the trends over the last twenty years are shown in Table III.

Year	UAE	Iran	Iraq	Kuwait	S. Arabia	Venezuela
1982	31.9	30.5	41.0	69.9	162.2	21.5
1984	31.8	30.4	43.0	95.4	168.0	24.9
1985	31.9	30.5	44.5	95.2	171.6	25.9
1986	31.4	30.0	44.1	97.2	170.2	25.6
1987	32.4	31.0	47.1	97.1	169.0	25.0
1988	96.2	92.9	100.0	94.5	172.6	58.2
1989	98.1	92.9	100.0	97.1	257.6	58.5
1990	98.1	92.9	100.0	97.0	260.0	59.1
1991	98.1	92.9	100.0	97.0	260.0	59.1
1992	98.1	92.9	100.0	97.0	261.5	62.7
1993	98.1	92.9	100.0	97.0	261.5	63.3
1994	98.1	89.3	100.0	97.0	261.5	64.5
1995	98.1	88.2	100.0	97.0	261.5	64.9
1996	98.1	93.0	112.0	97.0	261.5	64.9
1997	97.8	93.0	112.5	96.5	261.5	71.7
1998	97.8	89.7	112.5	96.5	261.5	72.6
1999	97.8	89.7	112.5	96.5	263.5	72.6
2000	97.8	89.7	112.5	96.5	261.7	76.9
2001	97.8	89.7	112.5	96.5	261.7	76.9
1996	58.7	64.7	77.4	60.2	222.6	27.4

Table III. Spurious Reserve Additions of Selected OPEC Members

The last line is an estimate by Campbell and Laherrère based on an industry database.

Kuwait started it in 1984 with a 36% increase. The United Arab Emirates and Iran boldly tripled their reserves and Iraq settled on a nice round number of 100 Gb. Not shown in the table is a figure for the Neutral Zone, which is located between Saudi Arabia and Kuwait and the production of which both countries share equally. During the 1980's the reserves of the Neutral Zone dropped from 6.1 Gb to 5.2 Gb. That the published reserves have not changed much from year to year in spite of significant production makes them untrustworthy. Still, these are the numbers on which the world relies for assessing future production.

The last line in the table is an estimate by Campbell and Laherrère based on their analysis using an industry database. As consultants to industry they have access to data that dates from the 1960's before the national oil companies of the Persian Gulf were formed. The discrepancy between the data supplied by the individual OPEC countries and their analysis is 225 Gb.

Since 1990 the world's remaining published proven reserves have been relatively flat at around 1000 Gb. Reserve estimation is a tricky art and there is no uniformity on how reserves are determined. How much is yet-to-find can be extrapolated from discovery trends, as Hubbert did to calculate the peak production for the lower-48 in the U.S. The oil endowment for the world appears to be between 2000 Gb and 2200 Gb. With 925 Gb produced so far, and if the spurious reserve additions are accepted, then there is still 275 Gb in the yet-to-find category.

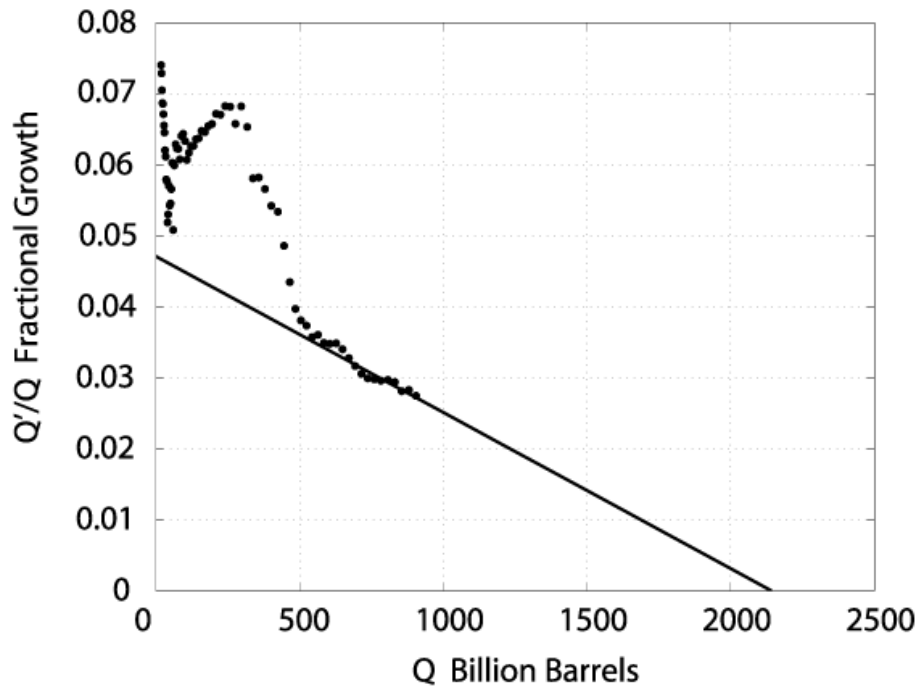


Figure 6: A plot to estimate the parameters for the Hubbert curves for world oil.

4.4 Prediction of the World Peak Production

The country by country analysis and the age of the giant fields are sufficient reason to worry about the nearness of the oil production peak for the world. More evidence that the peak is imminent is provided by logistic curves. The results are given below.

For the world the fractional increase in the cumulative production is given in Figure 6. The fractional growth rate $a = 0.0472$ and the ultimate is $Q_0 = 2200$ Gb. This leads to peak production in 2008.

Two annual production predictions are given in Figure 7. The upper graph is for the baseline prediction. For the lower graph the annual production was forced to have the value $Q_0 = 2100$ Gb, with the result that the peak production takes place earlier in 2006. Since the world production is roughly 25 Gb/a, each 100 Gb addition moves the peak year by 2 years. Thus the timing of the peak at today's production rates is quite insensitive to large additions in the ultimate production. The new discoveries in the Caspian region add only 40 Gb to the total [20].

Laherrère, the foremost oil analyst of the world, gives in Figure 8 the cumulative discovery and the cumulative production. The cumulative discovery has been properly *backdated*. That is, any additions to reported reserves of a given field are assigned to its initial discovery. The reason this ought to be done is to properly account for discoveries. Reserve additions do not come from new oil provinces, but from underestimation of existing reserves. When the backdating is done, world reserves are now decreasing, in contrast to the reported flat reserve figures cited in the BP Statistical Review of World Energy, 2001 [16].

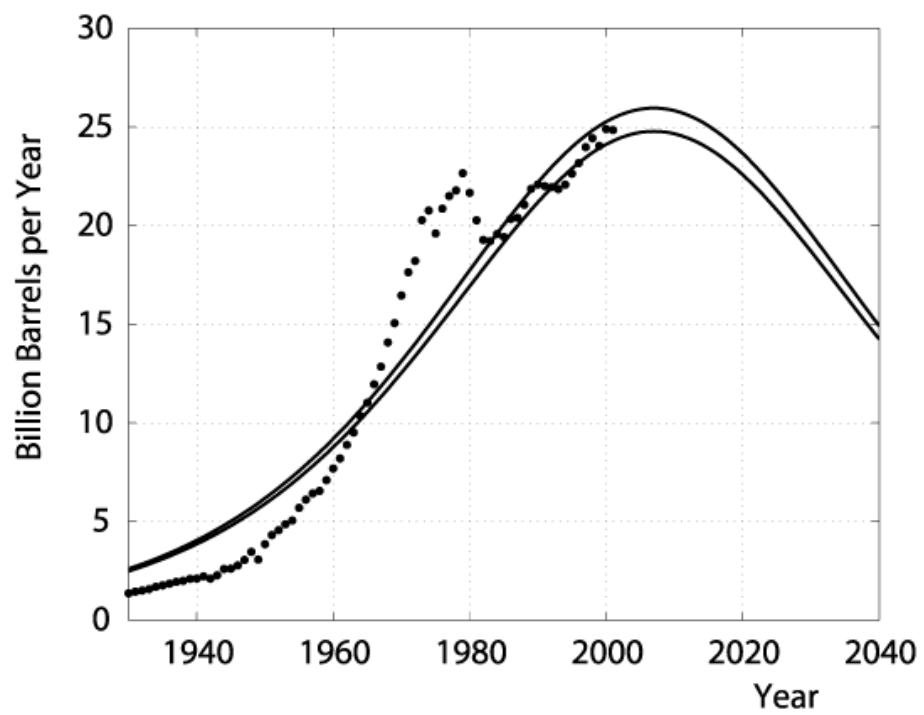


Figure 7: Two annual production curves for the world, the upper one with 2200 Gb oil endowment and a peak at 2008; lower based on 2100 Gb and a peak in 2006.

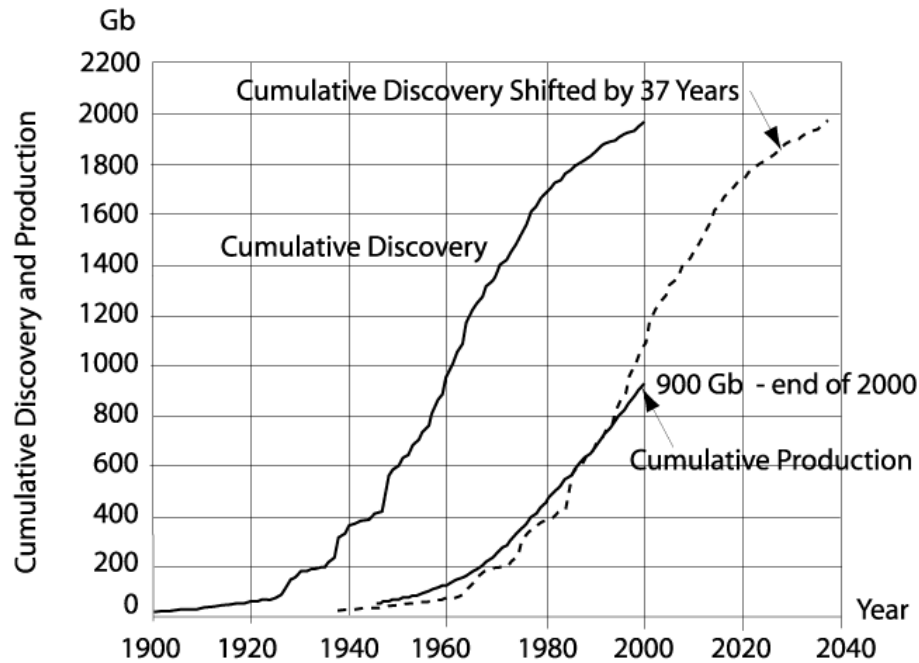


Figure 8: World cumulative oil discovery and production by Laherrère. [15]

It is clear that future production must mirror discovery, for oil must be found before it can be produced. This figure also shows that if the discovery is shifted forward 37 years, a reasonable agreement with the production trend is obtained.

In Figure 9 Laherrère gives his analysis for the likely production trends. It shows a higher peak than was found by the present analysis and initially a steeper decay after the peak has been reached, but any prediction of the downtrend is made difficult as the world economy, which is lubricated by inexpensive oil, may well seize, leading to a very jagged production trend on the downslope side of the curve.

Not much has been said about natural gas in this article, but Laherrère has studied its production and depletion as well. His analysis shows that the natural gas peak will come about 20 years after the oil peak. Its values are given in terms of equivalent amount of oil, in which one barrel of oil is equivalent to 5500 cubic feet of natural gas; that is 1 boe = 5500 cf. Since natural gas is a very clean burning fuel, it is the fuel that is now favored for new electric power plants. Its traditional use has been for home heating and manufacturing of fertilizer. North America is also experiencing rapid depletion of its natural gas reserves. The main natural gas provinces in the world are in Russia and Middle East. Natural gas is transported now mainly by pipeline, but a small portion moves today in liquefied form. This LNG accounts for about 3 % of the U.S. gas demand. The latest review of the world's global oil production peak, with Campbell's graphs of the total hydrocarbon production trends, is provided by Bentley in the journal *Energy Policy* [21].

During the next couple of years there will be a drilling boom in the deepwater Gulf of Mexico, Gulf of Guinea, and Campos Basin off the coast of Brazil, but as production wanes

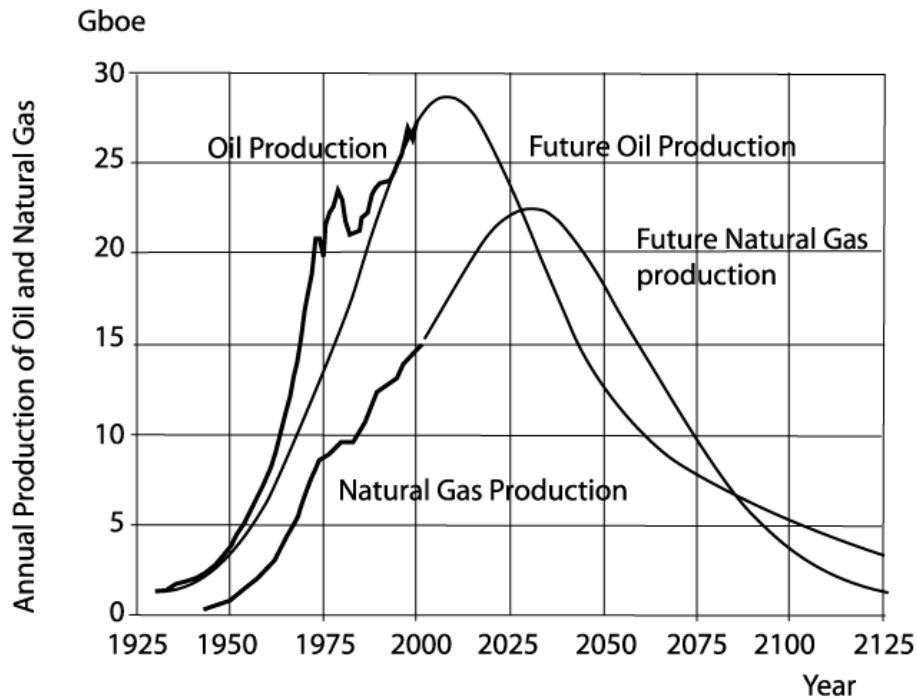


Figure 9: World production of oil and natural gas by Laherrère [15].

from these provinces, the only oil regions left are the ultra-deep oceans, the polar regions, and the South China Sea. It is unlikely that there is much oil in Antarctica, as the crustal plates have moved the continents northward. Also the hydrocarbons in the polar regions appear to be in the form of gas.

An important question for the next few years is how much Saudi Arabia will invest in new production [29]. The events of the last year are not favorable to investment. However, Saudi Arabia needs to invest to increase its revenues in order to support a population that has grown from 6.2 million in 1970 to 22 million in 2000. The Saudi government relies on oil revenues for 85% of its budget. The more than three-fold increase in population is reflected in the decrease in oil revenue which stood at \$2,600 per person in 2001, in contrast to \$24,000 in 1980.

There are deposits of heavy oil in the Orinoco region of Venezuela and in Alberta in Canada. The Orinoco operations are already producing more than 200,000 barrels a day, and output is expected to triple by 2006. Canada produces 400,000 barrels per day [22] [23]. Heavy oil production is more like a mining operation rather than traditional oil production. For this reason it is unlikely that heavy oil will be produced rapidly. Besides, in Canada the energy to produce these oils comes from *stranded natural gas*, stranded because there are no pipelines to bring it to markets. When the stranded gas is depleted or piped to market, energy to produce this oil must come from the final product itself, cutting the economies and certainly the energy returned for the energy invested [3].

5 Human Predicament

Although the oil industry is not yet willing to discuss frankly the imminent peak in oil production, a few industry insiders have made statements to this effect. Franco Barnabe, the CEO of ENI SpA announced in 1998 that the end of the oil era was in sight. The following year Mike Bowlin, the CEO of ARCO said that the oil industry was in its twilight. British Petroleum changed its logo during the summer of 2000 and now BP stands for Beyond Petroleum. Shell announced during the fall of 2001 that it was getting ready for the end of the oil era.

World oil consumption is now growing at about 1.7% a year and theory suggests that production will decay at about this rate at first and then faster after the peak. This means that depletion will take over a million barrels a day out of the market each year. This is comparable to the amount OPEC puts in or takes out of the market to control the price of oil. The difficulty is that each year after the peak oil production will decline in a world that demands an increase in supply.

There seems to be no way out of the predicament into which humanity has managed to get itself. In searching for insights on where the world is heading one may note what Harrison Brown penned 50 years ago.

... within a period of time which is very short when compared with the total span human history, supplies of fossil fuels will almost certainly be exhausted ... We are quickly approaching the point where, if machine civilization should, because of some catastrophe, stop functioning, it will probably never again come to existence. It is not difficult to see why this should be so if we compare the resources and procedures of the past with those of the present.

He then goes on to say that whereas high-grade ores and fuels were available to our ancestors, the low-grade ores and energy sources would not power a machine culture of the kind we have today [24].

During the last thirty years, owing to concerns of pollution and the oil crisis of the 1970's, ecology has risen to be an important discipline. Although in the public mind ecology is associated with attempts to save dwindling habitat for vanishing species, its deeper questions aim to make sense of what Charles Darwin called the *web of life*. Since organisms, as they multiply, change their own environments, insights from dynamics of growth and decline of organisms can be used to understand the human condition. Our predicament stems from our *inventive abilities*. It has allowed the world population to explode, from about a billion in year 1800 to six billion in 2000, the last doubling from three to six billion having taken just forty years. During this period many have moved from rural villages to huge mega-cities that have emerged during the last forty years. They will not be safe places during the declining oil era.

The title *Overshoot, The Ecological Basis for a Revolutionary Change*, of a book by William Catton tells that its author believes that the carrying capacity of the planet has already been exceeded [25]. On its title page is summarized the main line of his argument. It begins from the notion of *carrying capacity*, which is the maximum permanently supportable load on the planet. Next he discusses the euphoric belief in limitless resources, which he

calls the *cornucopian myth*. This myth originates from the Enlightenment. With this belief the next stage in Catton's scenario is *drawdown*, which he defines as stealing resources from the future. The drawdown of oil resources has been the topic of this paper and its effects will be severe. The drawdown in coal and oil has made the growth of the past two centuries possible and has led to an *overshoot*, which he defines as growth beyond an area's carrying capacity. The final stage is the *crash* during which population diminishes by die-off. The logic of ecological principles is brutal. Efforts to alleviate their effects need to be undertaken urgently. The issue is no longer how to *solve the coming energy crisis*, but *how to cope with it*.

Historians and political scientists have their own frameworks to map out the evolution of societies. Among those who specialize in international relations are members of the *realists school*, who base their understanding of what is likely to happen in the future on how great powers have acted throughout history. After the cold war, the world has moved from a bipolar great power contest between the Soviet Union and the United States to a unipolar world in which the United States is the sole great power. Whether it will strive for world hegemony is a question that is now under scrutiny [27]. Historians remind us that major wars have been fought to gain access to resources. Oil was the main reason for the German thrust toward the Caucasian region during WWII, and the more recent Gulf War was about who controls the rich oil reserves of the Persian Gulf region. Oil and water resources are the central issues in Klare's [26] recent book entitled *Resource Wars*. World events during the last year certainly point to increasing conflicts over natural resources. These and what petroleum geologists have written are a good guide for those who struggle to understand world events today.

In contrast to the views of Catton and Klare, economists are generally more sanguine about depletion of non-renewable natural resources. They assert that once the easily obtainable oil has been produced, prices rise to make the reserves not profitable at lower prices economical. Furthermore, they claim that increases in oil prices cause substitution of other forms of energy for oil. In contrast to the realists, be they petroleum geologists, ecologists, or political scientists, economists have constructed a highly abstract view of man. Such a view will not hold, as it continues to ignore what are called externalities and physical constraints. It is one thing to apply the principle of substitutability to replacing copper by fiber optics, it is quite another to substitute coal and solar energy for oil and natural gas. The former leads to increasing acid rain and destruction of the human habitat and low intensity of sunlight presents a special difficulty to its use on a large scale. Many economic models are descriptions of economic variables between equilibrium states. Depletion of natural resources is likely to lead to a new equilibrium at much lower level of quality of life, but this tends to be ignored as belief in substitutability and limitless growth still dominate economic thinking. Besides, many economic models are silent in regard to the time over which a transition between two equilibrium states takes place. Simulations of ecosystems show that transitions are often dramatic with a sudden reduction in population. The simulation of human activity that gained prominence in the 1970's are described in the book *Limits to Growth* [28]. Many of its predictions are yet to be played out.

In the arena of public discussion the pessimistic camp on the future of oil production is at a certain disadvantage, as people, particularly during good economic times, cannot fathom

that storm clouds may be forming. Furthermore, it is generally more difficult to obtain a sympathetic hearing for a worrisome viewpoint than an optimistic one, as belief in progress, both technological and societal, seems to be universal. This article has nevertheless taken the side of the petroleum geologist and the ecologist that oil depletion will become a serious issue before the end of this decade.

6 Acknowledgements

In the study of oil resources I have benefitted greatly by articles collected at the website <http://oilcrisis.com> organized by Ron Swenson. Without its links to publications of Colin Campbell and Jean Laherrère, many of them would have been very difficult to find. As a result I have been able to discuss these issues via e-mail with both Colin Campbell and Jean Laherrère. I am grateful for their gracious patience in answering my questions. The story retold here is largely their story. An organization now exists to study the imminent peak in oil production. Its monthly newsletter can be found at <http://www.energiekrise.de/>.

I wish also thank Roger Blanchard, who has been tracking the North Sea and Alaskan production extensively and has reported it at <http://www.hubbertpeak.com/blanchard/>, and Walter Youngquist for providing new reserve and production data and for confirmation of some of the estimates cited in the article.

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