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Hubbert's Petroleum Production Model: An Evaluation and Implications for World Oil Production Forecasts

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Following Hubbert's successful prediction of the timing of US peak oil production, Hubbert's model has been used extensively to predict peak oil production elsewhere. However, forecasts of world and regional peak oil and natural gas production using Hubbert's methodology usually have failed, leading to the implicit belief that such predictions always will fail and that we need not worry about finite resources. A careful examination of Hubbert's approach indicates that the most important reasons for his success in the US were stable markets, the high growth rate of demand, ready availability of low cost imports, and a reasonable estimate of easily extractable reserves. This analysis also shows that his model cannot predict ultimate oil reserves and that it should be considered an econometric model. Building on Hubbert's vital insight, that cheap fossil fuel reserves are knowable and finite, one can state that for world peak oil production, political constraints should be much more important than resource constraints.

KEY WORDS: Petroleum, oil, oil peak, Hubbert, Hubbert's Peak.

INTRODUCTION

Although it is understood nominally that petroleum and natural gas are not renewable resources, modern industrial society has been operating successfully as if they were. Economic growth, based on widely available, extremely profitable, and easily affordable fossil fuels, has been impressive in the developed world, and those nations that have not been part of this process, such as China and India, are now beginning to demand their share of these resources. Almost from the beginning of the US petroleum industry in 1859 there was speculation about when the US might run out of oil. Such dire predictions invariably had been proved wrong as new frontiers were opened up and new discoveries made. Perhaps the first of a continuous stream of warnings was by a Pennsylvania geologist, who in 1874 stated that the US would run out of oil by 1878 (Anderson, 1984). New fields in Indiana almost immediately voided this judgment, but this scenario was repeated time and time again in the future. By the late 1920s, the central problem was not shortages but oversupply and collapsing prices after the discovery of the gigantic East Texas field and the start of the Great Depression. Between 1929 and 1932, US demand dropped by 22% and prices dropped (Weaver, 1986) from over $1.15 per barrel (1930$) to $0.10 per barrel. Only the joint action of federal and state governments to create and enforce a system to proration (production ration) supplies to meet but not exceed demand restored order to the industry.

Coincidentally, this system forced prices to return to acceptable levels (which were a factor of 25 above production costs of the most efficient producers).

US petroleum supplies from the seemingly limitless fields in Texas were a major factor in the Allied victory in World War II. By the 1950s, with the US economy and oil consumption booming, the notion that the US might not be able to satisfy petroleum demand internally seemed far-fetched, and when US production finally did peak in 1970, this came as a surprise to those few people outside the industry who monitored petroleum production. Even today (2004),

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Table 1. Least-Squares fit for Logistic Growth Model For Given Q_{max}

Q_{max} (Billion barrels)	a	b (year^{-1})	r^2	t_{peak} (years)	Year
150	41.3	−0.0701	0.9991	53.1	1964
170	46.8	−0.0687	(Hubbert fit)	56.0	1967
170	46.2	−0.0685	0.9987	56.0	1967
225	59.9	−0.0659	0.9976	62.1	1973
250	66.1	−0.0651	0.9972	64.4	1975
300	78.7	−0.064	0.9965	68.2	1979
350	91.0	−0.0633	0.996	71.3	1982
400	104.0	−0.0628	0.9956	74.0	1985
450	116.7	−0.0623	0.9953	76.4	1987
500	129.4	−0.062	0.995	78.4	1989
600	154.8	−0.0615	0.9946	82.0	1993

after oil production has peaked or reached a plateau in the great majority of producing regions[2] around the world (e.g., USA, North Sea, China), those who maintain that world oil resources will not be able to satisfy demand far into the future are derided and scorned (Maugeri, 2004), although some in the industry have begun to acknowledge that demand could exceed supply in the near future (OGJ, 2004).

It is clear that the concept of limits to growth is difficult for most people to accept. Many decades of increased economic activity and spectacular progress in all areas of science and technology have created the impression that such a state of affairs is a permanent component of Western civilization. Yet limitations are a fundamental part of the natural order, and sooner or later we must face up to this. In particular, fossil fuel resources, an essential input into any modern economic system, are finite. Understanding this measurably and mathematically, not just qualitatively, is crucial if society is to cope with depletion of these resources. Examining the reasons for the success of the best known depletion model, that of Hubbert, in dealing with this problem allows one to determine if it is applicable to current conditions, and if not what might be appropriate.

LOGISTIC GROWTH CURVES

Hubbert (1956, 1962) was the first to treat the issue of depletion quantitatively and observed that cumulative production of an exhaustible resource as a function of time (t, years) usually (but not always) followed a logistic growth curve, given by

$$Q(t) = \frac{Q_{max}}{(1 + a \exp bt)}, \tag{1}$$

where Q_{max} is the total resource available (ultimate recovery of crude oil), $Q(t)$ the cumulative production, and a and b are constants. Production begins slowly, then grows exponentially, reaches a maximum and then declines. A characteristic of this equation is that it is symmetric about the point of maximum annual production, and that the rate of rise and decline are identical.

Maximum annual production is given by

$$P_{max} = \frac{Q_{max}|b|}{4}, \tag{2}$$

the year of maximum annual production by

$$t_{max} = \left(\frac{1}{b}\right) \ln \left(\frac{1}{a}\right) \tag{3}$$

Hubbert plotted US crude oil production data from 1911 to 1961 on semilog paper and determined the parameters a, b, and Q_{max} in Equation (1) that best fit, according to his judgement, these data; at the time, this methodology was perfectly acceptable. He determined $Q_{max} = 170$ Bb (Billion barrels), $a = 46.8$, and $b = -0.0687$ (listed in Table 1), with a base year of 1910.5.

This type of equation can be fitted to these data using parameters with many different values, and with modern techniques, goodness of fit can be determined quantitatively. Hubbert's data set (Fig. 1) has been regenerated (API, 1951; DOE-EIA, 2003); for 150 Bb $< Q_{max} <$ 600 Bb, the values of a and b and goodness of fit (r^2) have been determined using the Trendline option in Excel. Results are listed in Table 1. Note that Hubbert's fit is reasonable; for his Q_{max}, the

[2]Oil production has peaked or reached a plateau in 68 of 99 producing countries [Smith, M. R., 2004, quoted in Oil & Gas Journal, 2004, v. 102.20 (May 24), p. 7].

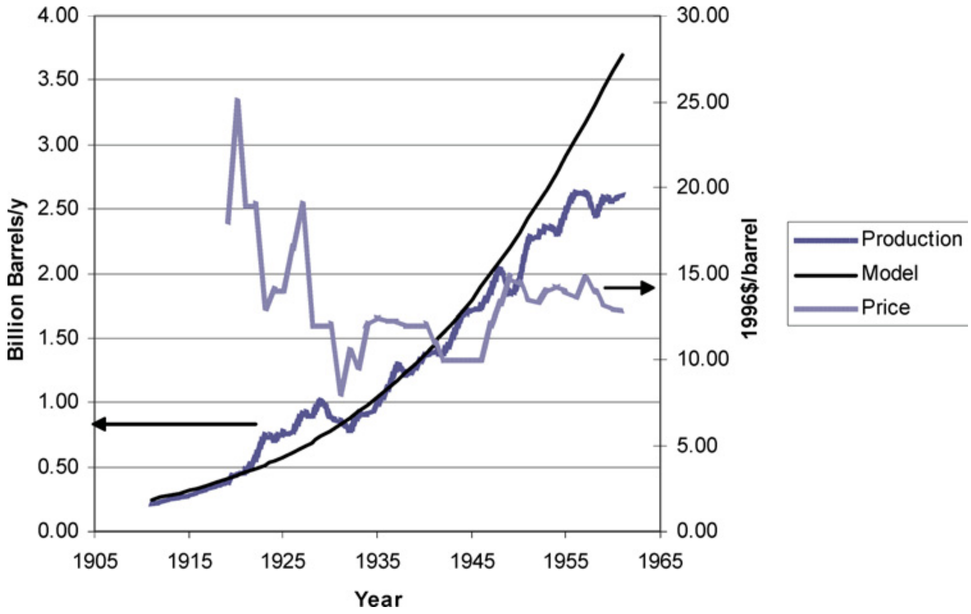

Figure 1. Hubbert's data set for US oil production, logistic growth curve model (shown for $Q_{max} = 350$ Bb, $r^2 = 0.996$), and annual average oil price, (1911–1961).

parameters a and b are close to those obtained from the fitting routine with an r^2 of 0.9987.

However, for the range $150 < Q_{max} < 600$ Bb (Table 1), the goodness of fit differs only in the third decimal place, with $0.9991 > r^2 > 0.9946$; the model result for $Q_{max} = 350$, a factor of two greater than Hubbert's choice, is shown in Figure 1. This should be expected with an exponential equation with three free parameters; based on goodness of fit, there is no reason to select any one of these numbers for Q_{max}. This reflects a fundamental reality: past production/consumption cannot predict the total amount of oil that is in the ground. Hubbert's assertion that his curve fitting to past production could reveal ultimate oil reserves is not justified.

The best fit to the data is given by $Q_{max} = 150$ Bb ($r^2 = 0.9991$), yielding a peak year of 1964, only a few years from the date of Hubbert's publication (Hubbert, 1962). At that time, US oil production was 7.1 Mb/d (million barrels per day), but shut in capacity[3] (as Hubbert noted) was 3.6 Mb/d, and, as will be discussed later, many US producers wanted to increase production as rapidly as possible. There was no indication that there would be a peak in production because of resource constraints in the immediate future; thus, the lowest estimate of ultimate oil reserves could be rejected.

This emphasizes the importance of independent estimates of reserves. To be relevant, they must be made assuming a certain minimum level of profitability and current technology or reasonable extensions thereof. The farther into the future one attempts to see, the higher the risk, because at a minimum technology, if not market price, will advance and enable more oil to be recovered at a given price (or so it seemed in 1961).

Hubbert estimated ultimate oil reserves in two other ways. He reviewed 14 independent reserve estimates made between 1956 and 1961 (Fig. 2). Seven estimates were between 145 and 200 Bb, three between 200 and 300 Bb, and the other four between 300 and 600 Bb. The methodology used to obtain these different estimates is discussed in only one instance; some estimates were made by teams of oil company geologists, whereas others may have been simplistic approximations. At this time, such efforts were more art than science, and followed more from educated guesswork rather than rigorous analysis.

Hubbert also estimated Q_{max} using logistic growth curves as applied to large and small field discovery. He admitted that this approach, although it agreed with other results, was "valid as to order of magnitude" accuracy, and believed that

[3] Hubbert (1962) defines this as the difference between maximum well output (regardless of availability of pipeline capacity or storage facilities) and allowed production (as determined by need to meet demand and maintain high prices).

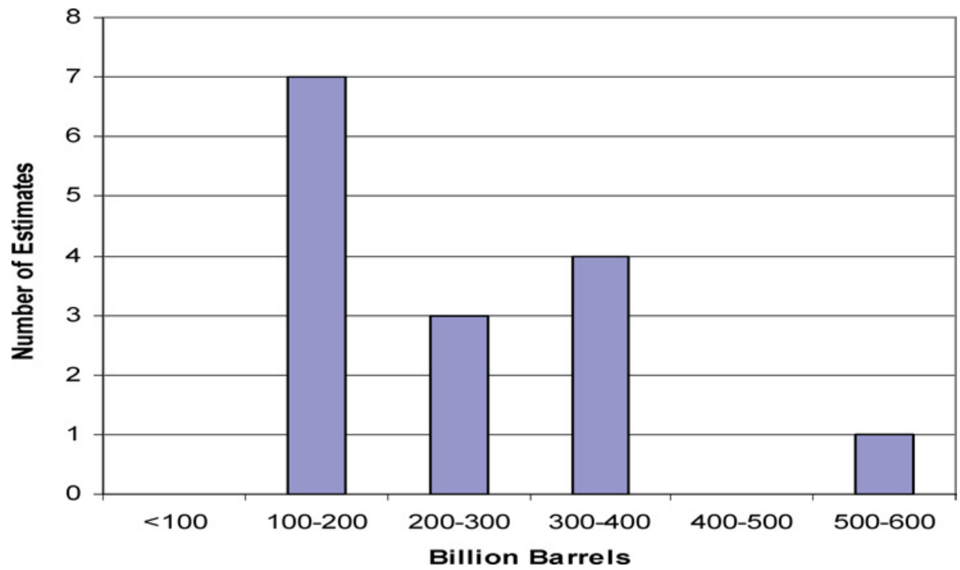

Figure 2. Estimated ultimate US crude oil reserves cited by Hubbert (1962).

the curve fit to consumption/production was more reliable.

His selection for Q_{max} (170 Bb) was in agreement with the great majority of reputable experts at the time; he also noted that Q_{max} might be as large as 225 Bb, and so his estimate for the year of peak production fell between 1967 and 1973 (Table 1). As noted previously, given the massive spare capacity in the US oil industry at the time, making such a forecast was an audacious move.[4]

Hubbert had several factors in his favor when he made his prediction. He had access to reliable reserve and production data, which was needed by The Texas Railroad Commission and similar organizations in other states to keep US production aligned with demand (both to maintain reliable supplies, avoid waste, and keep prices far above production costs). This information was collected by US Government agencies as well as by the American Petroleum Institute, and was available to the public. These data showed that discovery rates far large fields had declined substantially, from about five per year in 1945–1950 to about one per year in 1950–1960, whereas production/consumption increased rapidly. To supply ever increasing consumption from a greater and greater number of smaller and smaller fields had a strong practical limit.

Most important of all, the rate of increase of demand was high. In the 1950s US demand for petroleum increased by 4.7% annually (doubling time 15 years) and in the 1960s by about 3.96% annually (doubling time 18 years). This put the entire system under great strain because not only does the number of wells need to increase, but also all the infrastructure associated with moving the oil to market must be expanded. For example, building new pipelines is a major undertaking; it may require years just to obtain the necessary right of way.

Lower growth rates allow for more improvements in technology, changes in market rules, and political upheavals, any one of which could render models and the forecasts based on such models invalid.

In 1972, shortly after US production peaked at about 9.4 Mb/d, demand[5] increased by 7.1% or 1.1 Mb/d to 16.4 Mb/d. US production had not kept pace so that by 1972 imports supplied about 27% of demand[6] (compared to 15.6% in 1958). Without

[4] The amount of US spare capacity relative to production during this period was enormous. To put this into perspective, in 2004 world oil production is 80 Mb/d; spare capacity would need to be 44 Mb/d to be equivalent to US conditions in 1962. To predict that US production would peak in less than ten years given this much spare capacity seemed at the very least completely unrealistic to most people.

[5] Demand is taken to be petroleum products supplied (DOE-EIA, 2003), which consisted of crude oil production, natural gas liquids (NGL), processing gains, and net imports.

[6] Demand for petroleum products was driven by the exponentially growing population and the rapid spread of suburbs enabled by universal availability of low cost, minimally taxed gasoline. At the time, no attempt was made to reduce demand by increasing taxes or mandating automobile fuel efficiency.

increased imports, US production might have peaked even before 1966, regardless of the value of Q_{max}.

Even if the easily accessible reserves had been as great as 350 Bb, peak production [at about 15 Mb/d, from Equation (2), lower than actual demand in 1973] would have been delayed by only 12 years, to 1982, according to Hubbert's model.

LIMITATIONS OF THE MODEL

Conventional petroleum deposits usually occur in stratigraphic or structural traps, or porous rock formations with an impermeable cap, generally at a depth of between 1000 and 15,000 feet. Natural gas may occur above and dissolved in the oil, or water (brine) may occur below. Flow out of a well is either gas driven or water driven, with flow rates determined by formation temperature and pressure, permeability, surface properties and porosity, as well as fluid composition and viscosity. In scientifically managed production, the natural reservoir pressure is maintained as high as possible for as long as possible. Once the reservoir pressure is insufficient to bring oil to the surface, it must be pumped from the reservoir; finally, secondary and enhanced oil recovery techniques such as carbon dioxide injection are used to extract more oil from the reservoir as flow to the wells diminishes.

It must be emphasized that there is no geophysical, physical or chemical law that compels cumulative production to follow Equation (1). The logistic growth curve has nothing to do with any of the physical and geochemical factors that govern oil flows and well productivity. Oil production instead is determined by a wide variety of physical, political, and economic factors. Although one cannot exceed the maximum possible flow rate, flow can be kept well below this maximum for a variety of reasons.

Yet Hubbert's model did predict the time interval when US oil production peaked. It is important to understand why it did succeed, and under what conditions Hubbert's model might be valid.

Some of the economic and political factors necessary for Hubbert's model to be applicable are

- affordable prices for consumers and good profitability for owners of the resource,
- stable markets (stable political and market rules),
- exponentially increasing consumption,
- perception of limitless resources by producers and consumers: availability of imports,
- reasonable estimates of the magnitude of the easily accessible resources (proven, undiscovered, and reserve extension) given certain extraction costs, profit levels, and technology developments over the forecast period.

These elements of what might be considered an econometric model with political constraints now will be examined in more detail.

Economics: Profitability, and Affordability

Oil production is a business. Producers want to make a profit, usually as much as possible as quickly as possible. There are buyers who must pay for the product and must be able to afford it. The market may be regulated or unregulated, but if prices are set too high, either to increase profits or for political reasons, and consumers cannot pay the price, consumption, and production, must decrease. If prices are set too low, there is little incentive to locate and produce oil, tasks which demand great skill and persistence in extremely hostile and treacherous environments.

An example of what happens when consumers cannot afford oil is illustrated by events in 1979 when the Iranian Revolution disrupted production in that country and prices abruptly rose to about $50/b (Fig. 3). The high oil prices caused US oil demand to drop by about 20% between 1978 and 1983, while world oil demand dropped by about 16%. The logistic growth model cannot handle this type of event.

When OPEC increased the price of oil far above the US domestic price in 1973 (Fig. 3), domestic production continued to drop, although not as rapidly as predicted by Hubbert's model. This is the result of a number of factors. One was the greater profitability of nondomestic oil production; in the early 1980s, exploration and production costs were at least 25% greater in the US than abroad (DOE-EIA, 2003). Another was that the most accessible resources (for the best technology available at the time) had been depleted (see Appendix).

Even today, with foreign and domestic exploration and production costs roughly comparable (about $5/b, and far below and the market price set by OPEC), US production continues to decline slowly, and there seems to be no possibility of domestic production satisfying demand. This pattern may be the result of companies' desire to preserve their domestic production base and take advantage of foreign opportunities while they are available.

An example of too low a price for producers is illustrated by the history of US natural gas prices and

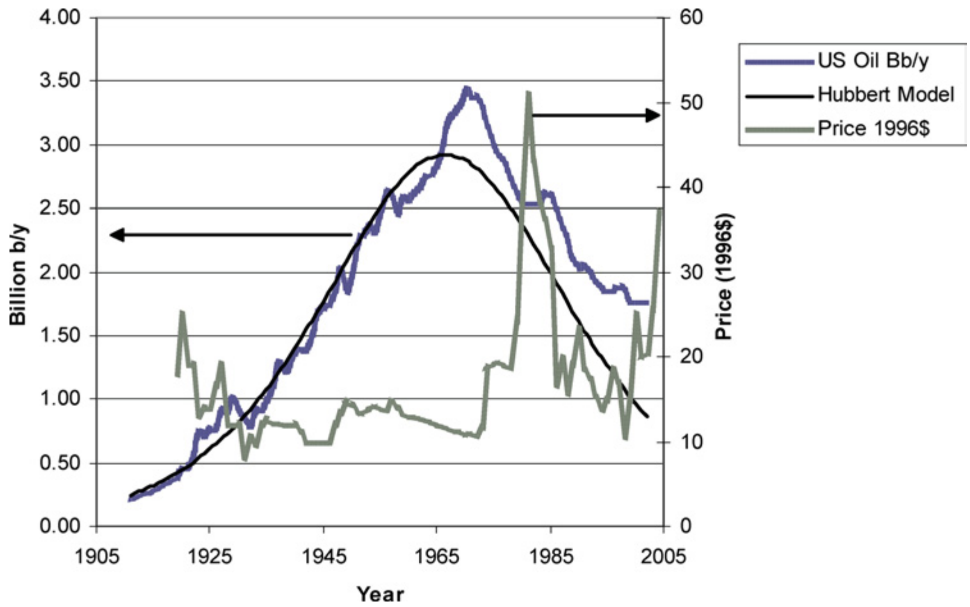

Figure 3. US Oil Production (Bb/y), US annual average wellhead price, 1996$, and production from a logistic growth model with $Q_{\max} = 170$ Bb (Hubbert's parameters, Table 1).

production (Fig. 4). The interstate price of natural gas was set by the Federal Power Commission, and in the 1960s was a factor of 3.5 below that of oil, on a per unit energy basis. Even with high pipeline and distribution tariffs, the cost to consumers was lower than oil. Most natural gas was produced as "associated gas," or as a byproduct of oil production. Once oil production peaked in 1970, natural gas production peaked shortly thereafter. With gas prices so low, there was little incentive to conserve or to produce more gas. Even worse, unlike oil, natural gas could not be easily imported. The only possibility that remained was "demand destruction" because of supply constraints, which proved to be extremely brutal.

Once natural gas prices to producers were allowed to rise—by nearly a factor of six between 1973 and 1983—production/consumption decreased significantly, but gradually stabilized as higher prices

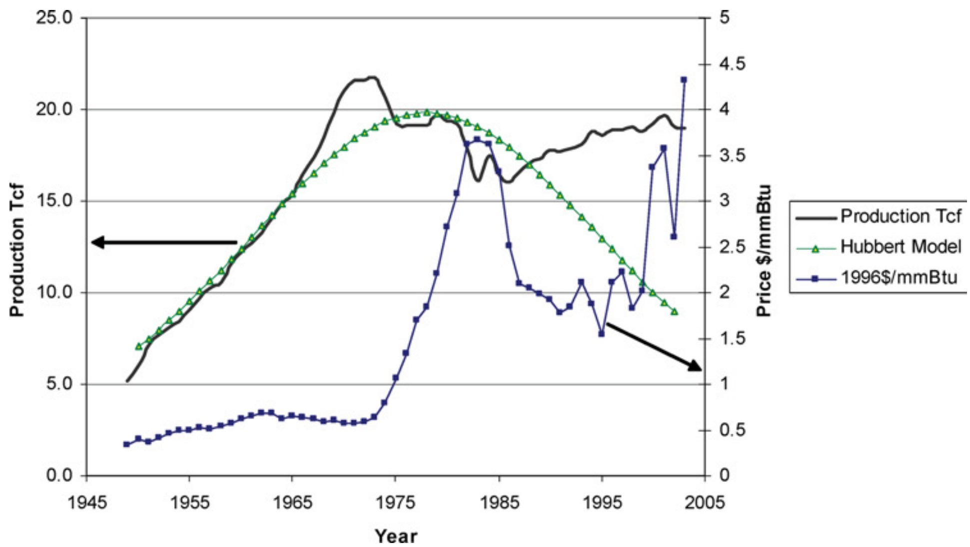

Figure 4. US natural gas production, wellhead price, and Hubbert model predictions.

provided the incentive to locate and produce more natural gas.

Hubbert estimated US ultimate natural gas reserves at 1000 Tcf from historical production data, following the same curve fitting methodology he used to estimate petroleum reserves. His model predicted the year of peak gas production at around 1976. As shown in Figure 4, this approach yielded a reasonable estimate of the peak production period. However, once gas prices increased, new resources became available and production is now about twice what the original model forecast. As with petroleum, a change in the economic conditions may (but not necessarily will) open up a greater resource base (see Appendix).

Stable Markets and Public Policy

The importance of public policy in setting market rules is evident from a careful examination of the production data used by Hubbert (Fig. 1), together with consumption data and an understanding of concurrent political battles. US production remained below 7.1 Mb/d between 1956 and 1961; petroleum consumption, on the other hand, rose from 8.8 to 10.0 Mb/d, a 12% increase, during this period. Even in 1958, during the second worst post-World War II recession (Gross Domestic Product declined by 1%), demand actually increased by 0.3 Mb/d while domestic production decreased by 0.46 Mb/d (−6.5%) and imports increased by 42% (from 1.007 to 1.425 Mb/d). Imports were readily available and made up the difference between US production and consumption.

Stagnant or declining US production was not caused by any resource constraints or delivery bottlenecks during this period, but by a ferocious struggle between the independent domestic oil producers and the major oil companies with access to inexpensive foreign oil, which could be landed at East Coast ports for prices 60–70% below that of US crude oil (Yergin, 1991). Voluntary import quotas, which had limited imports up to 1957, could not withstand such enormous price differentials, and simply began to be ignored. Meanwhile, domestic producers were forced to restrict production to maintain the high prices that produced such spectacular profits for others, a situation that was clearly untenable and unfair. The bitter dispute was resolved finally in favor of domestic producers (and against consumers and energy security); on 10 March 1959, the Eisenhower Administration imposed mandatory restrictions on petroleum imports, and US production began to increase once again.[7] Without these restrictions (new market rules), US production would have effectively reached a maximum not in 1970, but in 1957, only because it could not compete with low cost oil from the Middle East.

This also illustrates the importance of relative profitability in determining oil production. Domestic oil production certainly was lucrative, but the even greater profitability of foreign oil in the US market, with market prices set far above domestic production costs, would have certainly limited or eliminated any growth in the US industry regardless of resource availability.

Exponential Growth

Logistic growth describes many systems in which an exponentially increasing reaction or process is supplied by a limited resource; human and nonhuman population growth is one example of this phenomena.

However, exponential growth of oil demand is not a certainty. As noted previously, demand dropped substantially during the Great Depression and following the large price increases in 1979. Markets may saturate long before production is slowed by resource constraints because of other factors such as a change in market rules or exorbitant price increases. In many advanced industrial countries population growth is low or negative, removing a major cause of increasing demand.

Of course, even if demand does not increase, production of a finite resource will ultimately decline. Hubbert's model cannot handle this situation, and as demand growth declines, the concept of a resource constrained production peak as predicted by a Hubbert model becomes less and less useful.

On the other hand, if demand growth were to be extremely high, then other factors such as transportation bottlenecks from less accessible production regions might limit supplies, and again a Hubbert model would be irrelevant.

Perception of Limitless Resources: Availability of Imports

As noted (*Stable Markets*), imports played a central role in meeting US demand. Imports gradually

[7] OPEC also tries to maintain oil prices far above production costs, but, unlike the Texas Railroad Commission, does not have any mechanism for resolving disputes analogous to this one.

rose from about 15.6% of demand in 1958 to 21% in 1970, when US oil production peaked. After 1970 imports rose even faster. Without imports, domestic production would have peaked earlier and more abruptly, as soon as domestic demand increased faster than production could increase, regardless of the size of the US ultimate oil resource. When demand, driven by increased economic activity, exceeded supply, even by a small margin, the market rules certainly would have changed as prices climbed rapidly to force demand down.

Readily available, low cost imports allowed the illusion of unlimited supply to continue, postponing the day of reckoning when consumers would be forced to acknowledge that petroleum was indeed an exhaustible resource. In actuality, the US production peak passed unnoticed by US consumers, who continued to increase demand as if nothing had happened.

Reserve Estimates

As of 2002, cumulative US oil production (lower 48 states only) was about 170 Bb, and this continues to grow at a rate of about 1.76 Bb/y (Fig. 3). The US Geological Survey (USGS) (Ahlbrandt, 2000) estimated that US ultimate resources (mean estimate, proven, undiscovered and reserve growth, as of 1/1996) were at least 360 Bb (including natural gas liquids), and recent discoveries[8] in the deep waters of the Gulf of Mexico may increase this by as much as 29 Bb (DOI-MMS, 2001).

That current estimates of ultimate resources (now including Alaska and deep water) are so much greater than Hubbert assumed was irrelevant for the purpose of understanding when peak production might occur, which depends on how much accessible oil is available for the period of interest as well as on many political and economic factors. For example, the technology needed to extract oil from the deep waters of the Gulf of Mexico did not exist when Hubbert made his prediction. In addition, much of the US resource was in the form of "reserve growth," or petroleum that is extracted from existing fields using infill drilling, field extensions or new enhanced recovery technologies. This oil can be extracted more slowly compared to the early production from a field.

With regard to natural gas production (Fig. 4) the USGS (Ahlbrandt, 2000) estimates that conventional gas resources (mean estimate, proven, undiscovered and reserve growth, as of 1/1996) were about 1900 Tcf, with substantial additional resources available as "unconventional reserves" in coal beds, tight sands and shales. As with oil production, these higher resource estimates were irrelevant for estimating the time frame for peak production. Only easily accessible resources capable of meeting rapidly increasing demand at a given price are relevant to this issue.

APPLYING HUBBERT'S MODEL TO WORLD OIL PRODUCTION

A crucial input to any model used to forecast world oil production must be credible world petroleum resource estimates. Until recently, these did not exist in an accessible form, and forecasters were dependent on statements of proven reserves of dubious veracity from producing countries and companies, or on proprietary data bases unavailable to the general public. Moreover, proven reserves are useless for predicting future production trends; for example, the US has had proven oil reserves equivalent to about ten years of production for the past thirty years or more (DOE-EIA, 2002), and continues to produce large amounts of oil.

Growth of world oil consumption between 1990 and 2002 was about 1.2% per year, which yields a doubling time of 58 years. If these growth rates were to be maintained, and all producers cooperated completely, the ability of a Hubbert model to predict future production peak would be questionable. A production plateau many decades in duration might occur, giving the illusion that such a state could persist forever.

The issue of producer cooperation is central to this question. In the US, as production approached a peak, domestic producers could not satisfy all of the incremental demand and imports made up the difference. Domestic producers continued to increase production because if they did not their output share would be taken up by imports, reducing current income. That real domestic prices were declining after 1957 (Fig. 3) because of

[8] Resource assessments typically have been made assuming an oil price of $18 per barrel. Currently (6/2004) prices are nearly twice this level, which should further increase the resource base (see Appendix).

competition from low cost oil from the Middle East made their decision easier. In other words, US producers made rational business decisions based on their available resources and the then-current market rules.

For the situation of world oil production, business decisions will be made based on a different set of rules. As noted earlier (Footnote 3), many producers already have reached a plateau or decline in production. Remaining producers now must increase production not only to satisfy increasing demand, but also to compensate for production declines elsewhere. At some point it will become apparent to these producers that it makes perfect economic sense to ration a scarce resource by increasing the price, reducing demand accordingly. The timing of such a transition will depend much more on the distribution of resources (including transportation resources) among the remaining producers and their respective economic and military power rather than on any inherent resource constraints on production.

Transportation constraints already are limiting deliveries from Russian producers. Russian oil shipments through the Bosporus (Clark, 2004) are being delayed because of nighttime navigation restrictions on large tankers. This shipping route, which passes through Istanbul with a population of 10 million people, would be closed by a major accident. The pipeline network through which most of Russia's oil is exported also is reaching its maximum capacity. Russian oil exports now are a major factor in world petroleum markets; production increased by about 0.8 Mb/d (11.2%) in 2003. A similar increase is expected in 2004, but not in 2005 because of these bottlenecks.

In 2003, demand, driven by the rapid industrialization of China and India, increased by 2.55 Mb/d, or 3.9%; 64% of this increase was supplied by OPEC, with the remainder supplied by Russia. In the first quarter of 2004, oil demand in China increased at an annual rate of 1 Mb/d (Adkins, 2004). Such extraordinary increases in demand can only be supplied by the Middle East. Yet Saudi Arabia, with a current maximum production capacity of about 10 Mb/d, is planning to increase its capacity to 12 Mb/d only after 2010 (Lorenzetti, 2004).

Thus, the world may be facing an imminent peak in production in the immediate future determined not by fundamental resource constraints but by transportation limitations and producer determined limits on production.

CONCLUSIONS

Although Hubbert's model may be applied in an operational sense to forecast peak world oil production, it should at the least be accompanied by a discussion of the assumptions and limitations of this approach. In addition, the parameter $Q_{\max}$ should not be interpreted as representing the ultimate oil resource, as assumed by Hubbert, but as a free parameter that represents the most easily accessible resource (given technological, political, and economic constraints). Indeed, given the importance of economic and political factors in oil production, Hubbert's model should be considered an econometric model, with its applicability determined by how well the conditions listed are satisfied.

Some forecasters (Campbell and Laherrere, 1998; Deffeyes, 2001; Ivanhoe, 1995) have used proprietary reserve data in conjuction with Hubbert's model or derivatives of this model to estimate future world oil production trends. It now is possible to use publicly available resource estimates based on the best available science and technology (Ahlbrandt, 2000) and different modeling approaches to estimate a peak year for world oil production (Cavallo, 2002; Green, Hopson, and Li, 2003); all of these approaches indicate that one should expect a peak in conventional world oil production as a result of resource constraints alone by 2025 or earlier.

However, producer cooperation is critical requirement for the validity all of these models. Given the political factors associated with current world oil production, it is essential that anyone interested in future world oil production make some attempt to evaluate the likelihood of continued cooperation as an increasing number of producing basins reach maturity and begin to decline. It seems increasingly clear that this factor, not resource constrained production, will actually determine the time frame in which petroleum supply will not match demand.

Finally, the central importance of Hubbert's model must be emphasized, whether or not it is currently applicable to world oil production. By mathematically predicting the time frame in which production of an exhaustible resource would be unable to meet demand, it challenged the unstated assumption of consumers and producers that such an event was beyond our ability to understand and that the petroleum industry could be trusted to meet demand far into the distant future.

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REFERENCES

Adkins, M., 2004, Quoted in Industry Trends: Oil & Gas Jour., v. 102.19, p. 7.

Ahlbrandt, T. (Project Head), 2000, US Geological Survey, world energy resources, world petroleum assessment (2000): Available at www.usgs.gov or on CD ROM from the USGS.

API (American Petroleum Institute), 1951, Petroleum facts and figures 1950 (9th edn.): API, New York, p. 117, 490.

Anderson, R. O., 1984, Fundamentals of the petroleum industry: Univ. Oklahoma Press, Norman, OK, p. 23, 235.

Bird, K., and Houseknecht, D., 2001, Arctic national wildlife refuge, 1002 area, petroleum assessment, 1998, including economic analysis: USGS Fact Sheet FS-028–01, Available at www.usgs.gov.

Campbell, C., and Laherrere, J., 1998, The end of cheap oil: Scientific American, v. 278, no. 3, p. 78–83.

Cavallo, A., 2002, Predicting the peak in world oil production: Nature Resources Research, v. 11, no. 3, p. 187–195.

Clark, M., 2004, The Bosporus bottleneck: Petroleum Ecnomist, v. 71, no. 6, p. 28.

Deffeyes, K., 2001, Hubbert's Peak: The impending world oil shortage: Princeton Univ. Press, Princeton, NJ, 224 p.

DOE-EIA (Department of Energy, Energy Information Administration), 2002, US crude oil, natural gas, and natural gas liquids reserves: 2002 Annual Report, DOE/EIA-0216(2002): Washington, DC, 47 p.

DOE-EIA (Department of Energy, Energy Information Administration), 2003, Annual energy preview, DOE/EIA-0384(2002): Washington, DC, 376 p.

DOI-MMS (Department of Interior-Minerals Management Service), 2001, Outer continental shelf petroleum assessment: MMS-2001–036: Washington, DC.

Green, D., Hopson, J., and Li, J., 2003, Running out of and into oil: analyzing global oil depletion and transition through 2050: ORNL/TM-2003/259, Oak Ridge Nat. Lab., Oak Ridge, TN, (www.osti.gov/bridge), 103 p.

Hubbert, M.K., 1956, Nuclear energy and fossil fuels: API Conference, San Antonio, TX, (March 7–9, 1956). Later published as Publ. no. 95, Shell Development Co. (June 1956).

Hubbert, M. K., 1962, Energy resources: A report to the Committee on Natural Resources of the NAS-NRC, Publication no. 1000-D, NAS-NRC: Washington, DC, 141 p.

Ivanhoe, L. F., 1995, Future world oil supplies: There is a finite limit: World Oil, v. 216, no. 10, p. 77–88.

Lorenzetti, M., 2004, Saudis refute claims of oil field production declines: Oil & Gas Jour., v. 102.10, p. 24–25.

Maugeri, L., 2004, Oil: never cry wolf—Why the petroleum age is far from over: Science, v. 304, no. 21, p. 1114–1115.

OGJ, 2004, Editorial: Serious about depletion: Oil & Gas Jour., v. 102.32, no. 23, p. 17.

Weaver, J. L., 1986, Unitization of oil and gas fields in Texas: A study of legislative, administrative, and judicial policies: Resources for the Future: Johns Hopkins Univ. Press, Washington, DC, 555 p.

Yergin, D., 1991, The prize: The epic quest for oil, money, and power: Simon and Schuster, New York, p. 536–540.

APPENDIX: RESOURCE SUPPLY AND MONOPOLY MARKET PRICE: THE PRICE-SUPPLY CURVE

Even with higher prices, neither US oil nor gas production has ever exceeded the peaks attained in the early 1970s. This can be understood using a resource price-supply curve which shows the amount of the resource available for a given market price, given best available technology, reasonable returns on invested capital, and no political constraints on production (Bird and Houseknecht, 2001).

Since at least 1935, the market price of petroleum has been set above the lifting cost of the most competent producers, first by the Texas Railroad Commission and then by OPEC. Production was limited in order to meet but not exceed demand and maintain prices at the desired level. A hypothetical US Price-Supply curve (Fig. A1) illustrates the effect that setting a monopoly price above extraction cost would have on production. In this example 50 Bb of oil can be produced profitably at a market price of \$2.25/b, 100 Bb at \$3.20, and 200 Bb of oil at \$12.50, the market price set by The Texas Railroad Commission. The US low cost domestic resource base was so large relative to demand that for several decades no price increase was necessary. Lower cost imports from the Middle East allowed this system to function for an even longer period than might otherwise have been possible. However, when the low cost reserves are finally depleted, prices must rise without any warning much more rapidly than they would without monopoly control. In addition, when prices do begin to rise, there may be a smaller resource base available; in the example in Figure A1, only another 30 Bb remain at any price, making the transition to other sources of energy more difficult.

New technologies and higher prices may open up other areas for exploration that were not reflected in the original assessment. This has indeed happened in the US, with resources in the Arctic and beneath first the shallow and then the deep waters of the continental shelf becoming technically and economically available. However, even if this does happen, it is likely that these more inaccessible resources will be

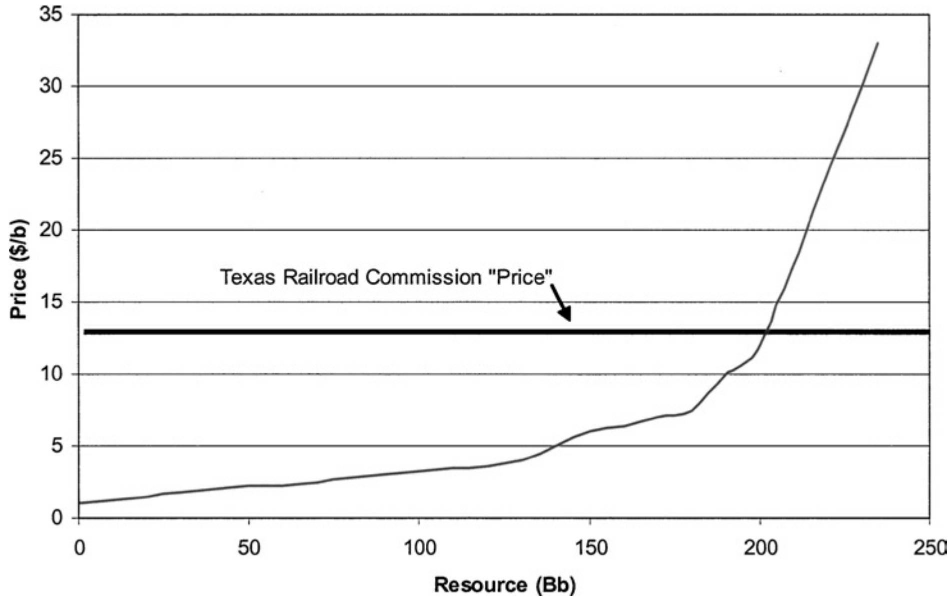

Figure A1. Hypothetical market price–(1996$) supply curve for US petroleum, as of 1962, with an assumed accessible resource (mean estimate) of 230 Bb.

able only to maintain production levels or decrease the rate of decline, not continue the exponential increase in production that the market demands.

Prices are not fixed arbitrarily. Ideally, they are set so that consumers easily can afford the product while providing excellent profits for capable producers. Consumers clearly pay large premiums over production costs, but given the lack of alternatives and the utility of petroleum, such are paid willingly.