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Review and Analysis of the Peak Oil Debate

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PREFACE

This report was prepared under an IDA Central Research Project titled "Alternative Energy Technologies."

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EXECUTIVE SUMMARY

The peak oil debate is concerned with the question of when global oil production will reach its historical maximum and enter a long inexorable decline. “Peakists” argue that oil production capacity is determined by geology and that global capacity will peak very soon—within a few years to a decade. “Optimists,” on the other hand, argue that economic factors overwhelm the geologic arguments and conclude that peak oil will not occur for many decades in the future. This paper reviews arguments from both sides, focusing the discussion on three topics. First, we review the Hubbert theory, examine its assumptions, and note the criticism levied by optimists. We present the results of our own modifications to Hubbert’s theory, which attempt to account for some of the critiques of optimists. In particular, we account for the impact of economic conditions on oil production in a simple, endogenous manner. Second, we review peakist arguments that are based on declining discovery rates. Finally, we include a section that reviews peakist concerns about Saudi Arabia’s oil production in particular as described in a book by Matthew Simmons. We conclude from these reviews that the most alarmist of the peak-oil claims are likely false. Still, we see some convincing reasons to think that global production could peak within 20 years, with demand outstripping production indefinitely.

I. INTRODUCTION

The current debate over "peak oil" is concerned with the question of whether global production of crude oil liquids will soon reach its historical maximum and enter a long inexorable decline, just as happened to U.S. oil production in 1971, as well as production of many other industries in history (e.g., whale oil, anthracite, etc.). So-called peakists, those who argue that the oil production capacity peak is imminent—within the next few years to a decade—generally subscribe to the Hubbert analysis (especially K. Deffeyes) or they argue on the basis of decreasing rates of oil discovery and other technical data, which they see as a harbinger of the imminent peak (C. Campbell, J. Leherrere, M. Simmons, etc.). On the other side of the debate are so-called optimists (e.g., Michael Lynch, the IEA, and various energy financial analysts etc.), who claim that the oil production is controlled by economics, not geology, and therefore conclude that such a peak will not occur for many decades in the future.

This paper reviews arguments from both sides of the debate and is divided into two main sections. The first section focuses on peakist arguments based on the Hubbert analysis of oil production, which is so named for M. King Hubbert, who correctly predicted that U.S. oil production would peak in the early 1970s. The second part reviews peakist concerns based on declining discovery rates and other technical observations. Along the way we provide some pieces of original analysis to complement our review and help support our conclusions: we are skeptical of an imminent peak within the next decade, but believe that a peak in conventional oil production is probable within the next 30 years. Such a peak warrants serious attention by stakeholders with a view out this far—including the military. Before diving into the two main sections of this paper, we begin with a review of some statistical terms and definitions that are used to quantify oil reserves and resources, since these quantities play such a central role in the debate.

II. ULTIMATELY RECOVERABLE RESOURCES

One of the central points of dispute between peakists and optimists is the question of how much oil is available to ultimately be recovered, called the ultimately recoverable resource (URR). Figure II-1 graphically describes the proper definition of URR and distinguishes it from the more widely reported (proven) reserves. The world's original oil in place (OOIP) is represented by the entire box, which is first ranked according to the quantity of oil that has been discovered (discovered at top). This is estimated by some (e.g., the International Energy Agency, IEA) to be near 10,000 Gbbl (10 Tbbl) for all hydrocarbons (IEA 2005). Its precise value does not matter much because we are concerned with the URR, which quantifies what fraction of OOIP that humans will ultimately be able to technically and economically produce when all the producing is done. The difference between OOIP and URR is the amount of oil that will remain unrecoverable despite all technical improvements the future may hold. The undiscovered portion is divided according to the amount that is thought to be discoverable in the future, called prospective resources, and the portion that is deemed undiscoverable (i.e., not accessible to humans). The upper section representing discovered resources is itself divided according to whether the resource is economically recoverable. Contingent resources are those that have been discovered, but are not economically recoverable, while "reserves" are economically recoverable resources. Divisions along the horizontal axis describe how certain the industry is that each fraction will be recovered. The commercial fraction itself is further divided into a fraction that has been already produced, called cumulative production (Q), and the remainder is called reserves. The reserves themselves are finally classified according to the degree to which they can be economically produced using current technology:

- Proved (a.k.a. P1 or P90)—90% probability that more than this fraction of oil can be produced economically.
- Proved + Probable (a.k.a. P2 or P50—50% probability that more than this fraction of oil can be produced economically.
- Proved + Probable + Possible (a.k.a. P3 or P10—10% probability that more than this fraction of oil can be produced economically.

The ultimately recoverable resource, URR, is designated by the red border and represents the fraction of OOIP that is thought will ultimately be recovered.

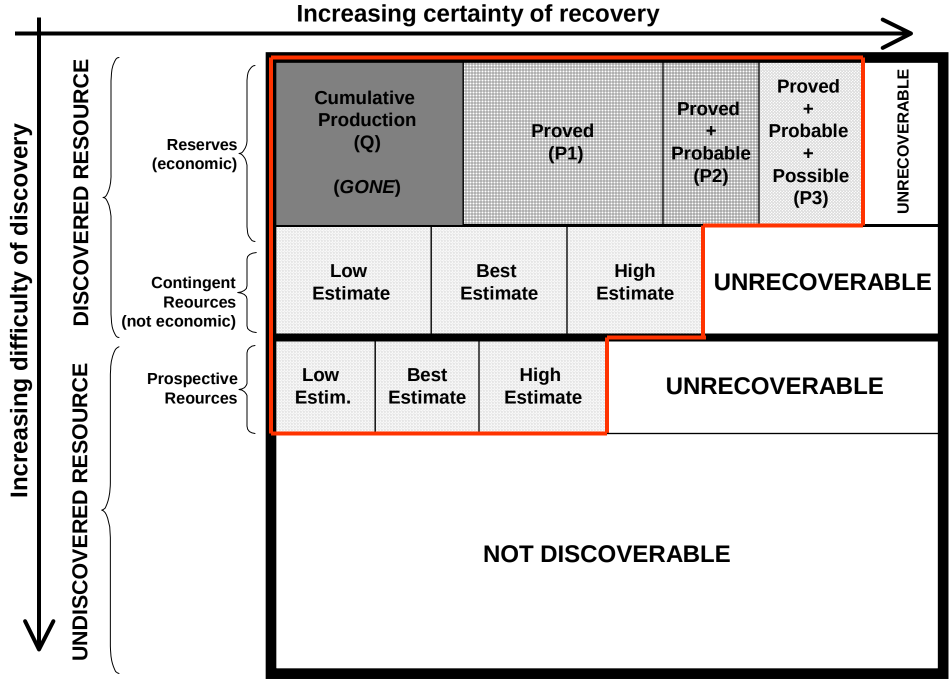

Figure II-1. Hydrocarbon resource classification scheme. (Source: based on Figure 3.7 in IEA 2004, pp. 81–127.)

Global proved resources are reported annually by various sources (e.g., *Oil and Gas Journal*, *World Oil*, *BP Statistical Review*, etc.), and the figures are fairly consistent across various sources. These data are supposed to be composed of P90 estimates, but this is almost certainly not always true.[1] Regardless, the important point to take away from Figure II-1 and this discussion is the difference between proven reserves and URR. Estimates of URR carry much more uncertainty than proven reserves, but URR, not

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1 One of the very important sources of disagreement and confusion in the debate over peak oil is the fact that various countries report their proved reserves figures using different levels (P90, P50, or P10). For instance, publicly held international oil companies report P90 reserves because of S.E.C. requirements and because it leaves a lot of upside for their reserves to appreciate, a development that pleases shareholders. On the other hand, national oil companies—and OPEC nations in particular—have an incentive to report higher reserves figures because it improves their apparent standing to potential creditors, and in the case of OPEC, the country's export quota is proportional to the size of their reserves. Reserves figures reported from these countries are probably P10 or perhaps higher. Because of such inconsistencies in reserves reporting, peakist J. Laherrere calls them "political" reserves, pointing out that such estimates are subject to politically motivated, systematic errors (Laherrere 2001, pp. 1–27). Two industry journals, *Oil and Gas Journal* and *World Oil*, are the main collectors of reserves estimates, which are then more or less repeated in secondary sources such as *BP's Statistical Review*, the U.S. Energy Information Administration (EIA). The International Energy Agency carries out its own surveys, but its data may suffer from similar difficulties (GAO 1999, pp. 1–18).

proven reserves, is the driver behind discussions of peak oil. Figure II-2 presents a series of estimates of URR made by technical geologic analyses over the last 65 years.

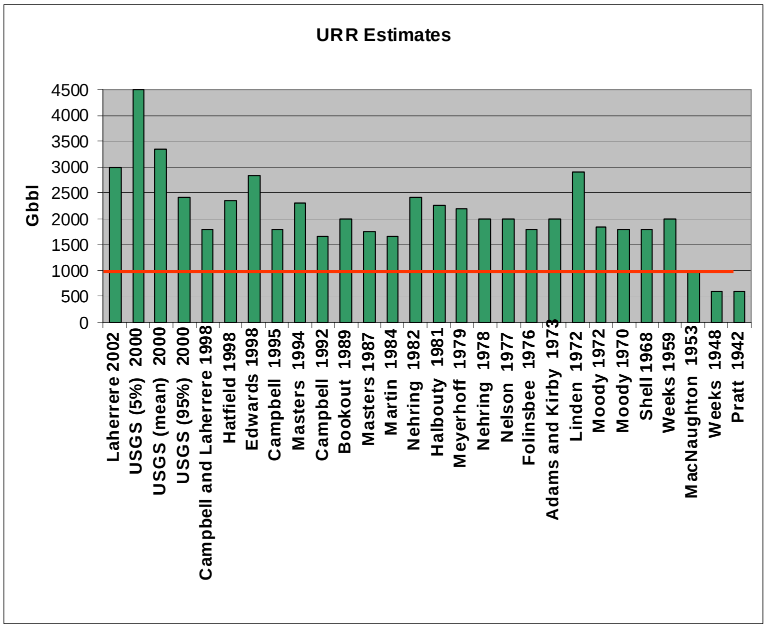

Figure II-2. Historical estimates of world URR made by various researchers over the past 65 years (Williams 2003, USGS 2000). The red line roughly represents total cumulative production to date.

Whereas recent proven reserves estimates vary by less than 15% from various sources (around 1,200–1,300 Gbbl), recent estimates of URR vary by at least 100%, ranging from around 2,000 Gbbl to over 4,000 Gbbl. Total cumulative production at present is generally accepted to be a little above 1,000 Gbbl, as shown by the red line. Consistent with their hypothesis that peak oil production is imminent, peakists in general contend that URR of conventional oil is around 2,000 to 2,500 Gbbl—that is, cumulative production is nearing half of URR, and proven reserves reports of around 1,200 Gbbl represent nearly all of the oil that is left, and little remains to be found (Laherrere 2001, pp. 1–27; Campbell and Laherrere 1998, pp. 78–84; Campbell 2003, Deffeyes 2005; pp. 1–201; Laherrere 1999).[2] Optimists, on the other hand, argue that URR is closer to 3,000 to 4,000 Gbbl. The USGS 5% estimate in (the year) 2,000 of 4,500 Gbbl (5% means there

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2 Another source of confusion and disagreement in this debate is the inconsistent definition of what kind of oil is included in URR. Peakists insist that the focus of peak oil concerns be on cheap conventional oil, while optimists point out that unconventional resources (e.g., heavy oil, tar sands, etc.) will expand URR as production technology improves—consumers don't care where their fuel comes from. In this paper, we understand URR to include conventional resources only; future contributions of unconventional fossil resources should be considered separately.

is a 5% chance that at least this much will be found) represents the highest estimate, and most other estimates lie between 2,000 and 3,500 over the past 40 years (IEA 2005; USGS 2000; EIA 2006a, pp. 25–35). Therefore, this paper will focus on the consequences of URR anywhere in the range of 2,000 to 3,500 Gbbl.

III. HUBBERT ANALYSIS OF PEAK OIL

A. THE HUBBERT METHOD AND SUCCESSFUL PREDICTION OF THE U.S. PEAK

Fundamentally, the Hubbert analysis of peak oil takes the entire complex system of oil production and asserts that the dominant factor is simply what fraction of URR remains unproduced—in other words, how much oil is left in the ground—geology. The argument does not say that technology, economics, and political realities do not affect production on shorter time scales, but its hypothesis rests on the idea that the amount of remaining oil dominates all other factors on longer time scales (Deffeyes 2005, Deffeyes 2002). This assumption is expressed in the differential form of the logistic equation, which forms the basis of the mathematical model used in the Hubbert analysis:

$$P = \frac{dQ}{dt} = aQ\left(1 - \frac{Q}{URR}\right), \tag{1}$$

where we see that production ($P = dQ/dt$) is directly dependent on the quantity *(1-Q/URR)*, which is the fraction of oil that remains to be produced. (*P* is production [bbl/year], *Q* is cumulative production—the total volume of oil produced thus far in history [bbl], *URR* is the ultimate amount of oil that exists to be recovered [bbl], and *a* is a rate constant with units of inverse time—the maximum possible production rate per barrel). M. King Hubbert, for whom this approach is named, developed this theory in 1958, based on his observations of oil production in the lower 48 U.S. states. These data from 1920 to present are shown in Figure III-1.

Hubbert observed that if the time series of production, *P*, is divided by cumulative production to date, *Q*—that is, if *P/Q* is plotted against *Q* itself—then an approximately linear relationship emerged in the U.S. production data, as shown in Figure III-2.

Such a linear relationship is in agreement with equation 1, which can be rearranged to the expression,

$$\frac{P}{Q} = -\frac{a}{URR}Q + a\ , \tag{2}$$

which is a simple first-order polynomial with slope of *–a/URR* and *y*-intercept equal to *a*.

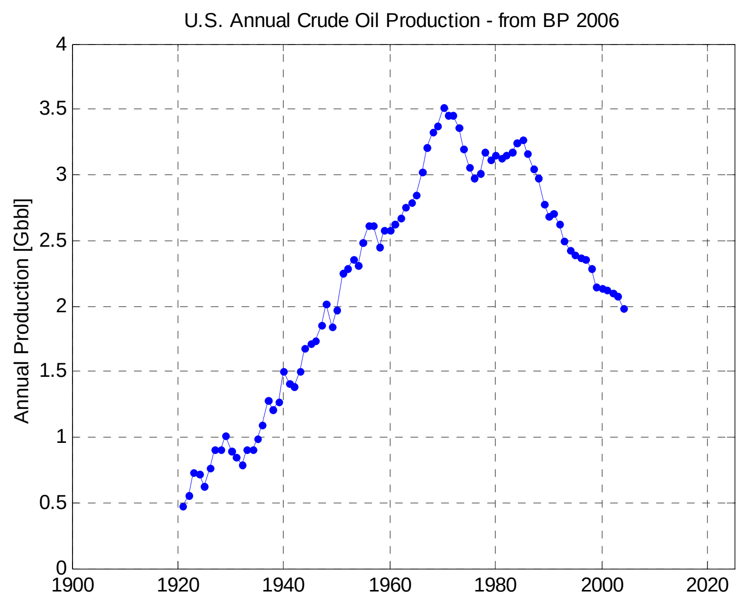

Figure III-1. U.S. Crude oil production from 1920 through 2005. (Source: EIA 2006b.)

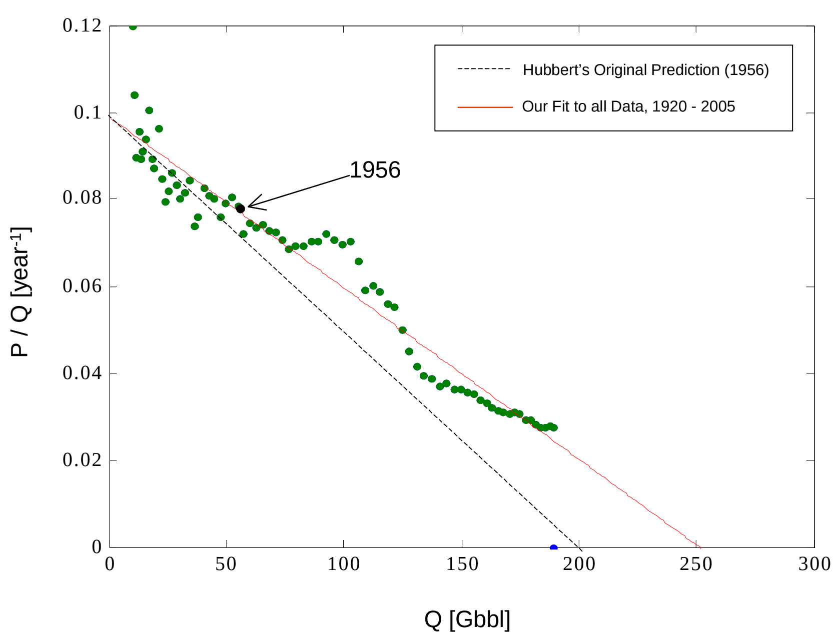

Figure III-2. Hubbert plot of annual production, *P*, divided by cumulative production, *Q*, of crude oil in the United States, vs. *Q* itself. This plot was generated using the same data as Figure III-1, beginning with 2 Gbbl of cumulative production in 1920. The red line represents a linear least squares minimization fit to the data shown here. The dashed line represents a line approximating the predictions made by Hubbert in the late 1950s based on data through 1956.

Realizing the linear trend in this data plot, Hubbert fit equation 2 to the data and simply extended the line to determine what the URR would be and when peak production would occur. The timing of the peak is obtained by solving the differential equation 1 for P to obtain the integrated form of the logistic equation,

$$P(t;a,URR,t_o) = URR\frac{\exp(-a(t-t_o))}{(1+\exp(-a(t-t_o)))^2}\,, \tag{3}$$

which is a function of time and of parameters a, URR, and t_o (the time of the peak). According to the algebra of this model, the production profile is symmetric in time, and hence the timing of the peak corresponds to the year that Q is equal to one-half URR. Based on the data available to Hubbert in 1956, the best fit line (dashed line, Figure III-2) predicts a URR of roughly 200 Gbbl and a production peak in the early 1970s. This prediction was realized with remarkable accuracy as shown by the full production history through 2005 in Figure III-1. Fitting equation 2 to the complete time series of U.S. production (1920 through 2005) yields a result that is quite close to that predicted by Hubbert in 1958.

B. WORLD PEAK PREDICTION USING THE HUBBERT METHOD

The remarkable success of Hubbert's analysis of U.S. production strongly suggests to peakists that the fundamental hypothesis of the analysis—that is, that the actual production of oil is governed by equation 1, which reflects geologic scarcity—is general and may be applied to the world as a whole. Figure III-3 shows world production of oil versus time, and Figure III-4 shows a plot of global P/Q versus Q, with both plots showing data from 1920 through 2005.

With the Hubbert analysis in mind the first thing apparent about the data in Figure III-4 is that the entire production history does not follow a straight line as well as the U.S. production history. However, peakists argue that the data eventually "settle down"—in this case after 1983—and a very good linear fit can be obtained, as shown in Figure III-4, with the projected line crossing the P/Q = 0 axis at about 2,250 Gbbl, which is the projection of this analysis for global URR (Deffeyes 2005). Recall that current cumulative production is a little more than 1,000 Gbbl, and it is clear that such a projection for URR implies that peak production (i.e., Q ~ ½URR) is imminent. Plotting the linear fit (red line, Figure III-4) against time according to equation 3, the peak would occur between 2005 and 2010 as shown in Figure III-5.

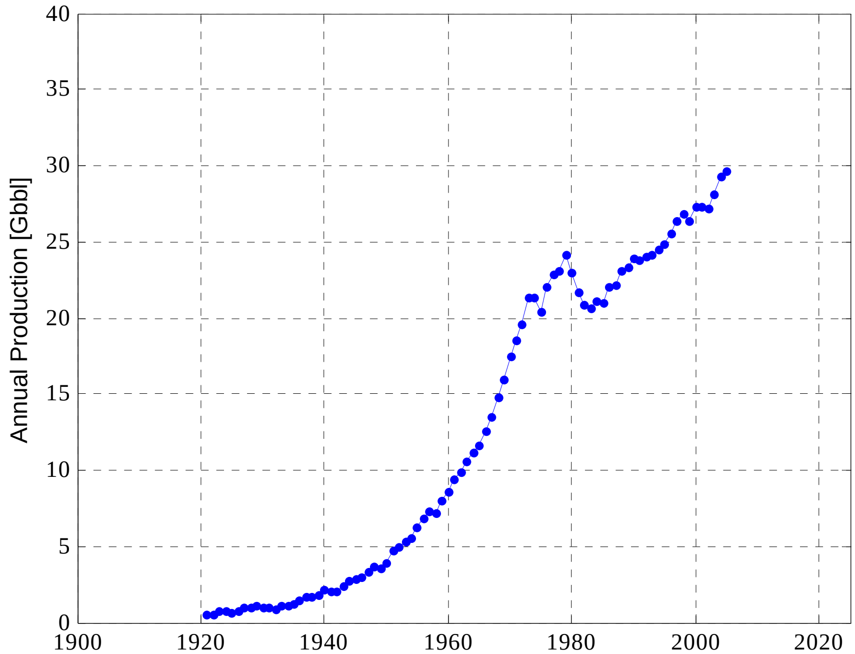

Figure III-3. Historical time series of the world's annual crude oil plus natural gas liquids production. Data from 1965 to 2005 from *BP Statistical Review 2006* (BP 2006, pp. 1–48). Data from 1920–1965 based on U.S. production of Figure III-1 and a linearly decreasing U.S. share of world market from 1920 (100%) through 1965 (25%).

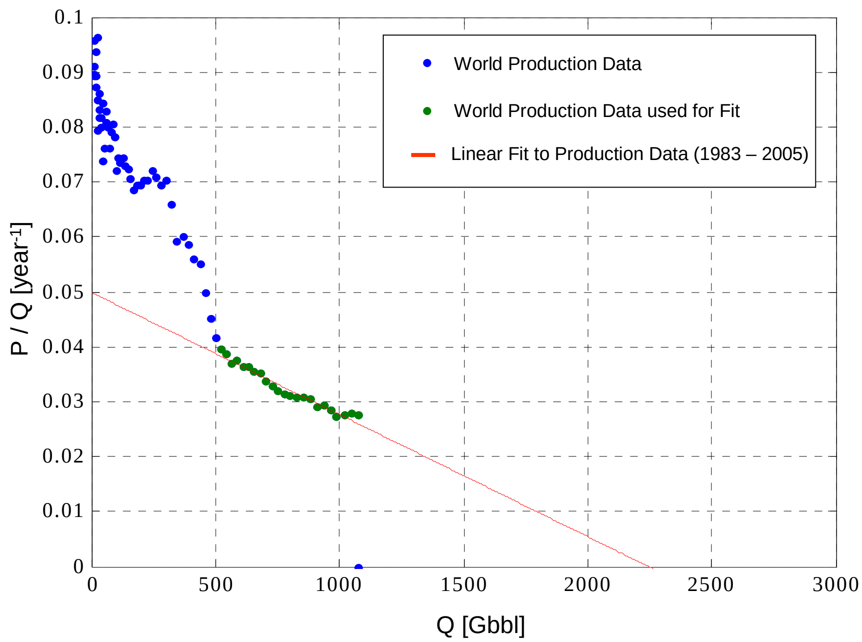

Figure III-4. Hubbert plot of annual production, *P*, divided by cumulative production, *Q*, versus cumulative production, *Q*, of crude oil for the entire world. This plot was generated using the same data as Figure III-3, beginning with 2 Gbbl of cumulative production in 1920. Blue dots represent the entire data set 1920–2005, and green dots represent the data over the period 1983–2005, which were used for the linear least squares minimization fit, given by the red line.

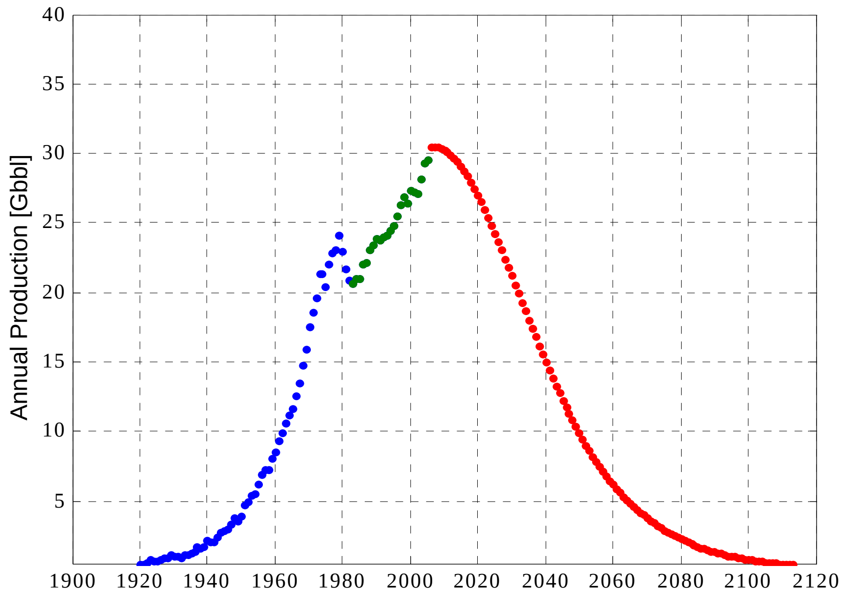

Figure III-5. Projection of world oil production based on the Hubbert equation and the fit to historical data obtained in Figure III-4 whose URR was 2,250 Gbbl. Blue and green dots represent the same data as in Figure III-4, and the red dots represent the projected production.

Because the foregoing analysis depends completely on a selective choice of what data are used for fitting to the model, in this case 1983 though 2005, the approach must be criticized for not explaining why the model does not accurately describe earlier production data points. One possible explanation—implied by the use of the phrase, "the data settle down"—is that for small values of *Q*, the stochastic error on the quantity *P/Q* will be much larger (error(*P/Q*) ~ sqrt(1/*Q*)) and will approach infinity as *Q* approaches zero. This explanation is not enough, however, because stochastic errors should result in data points scattered on both sides of the fit line, which is not the case. Another attempted explanation of the pre-1983 data looks to the dependence of these early data points on what value of *Q* is used at the beginning of the data series (Qstart). This parameter describes how much oil had been cumulatively produced before the beginning time in the time series, in this case 1920. It is indeed true that an injudicious choice of Qstart induces strange behaviors in the *P/Q* versus *Q* data, particularly a cusp as shown in Figure III-6.

For the world production data presented in Figure III-4, we used a value of Qstart = 2 Gbbl. In any case, though, the effect of Qstart is minimal on later data points and does not explain what caused the large change of the supposedly linear slope of *P/Q* versus *Q* around 1983. If such an explanation could be provided, then the core argument of Hubbertian peakists, namely, that there is no reason to expect a change in the slope of the linear fit in Figure III-4 (Deffeyes 2005), would be much easier to accept.

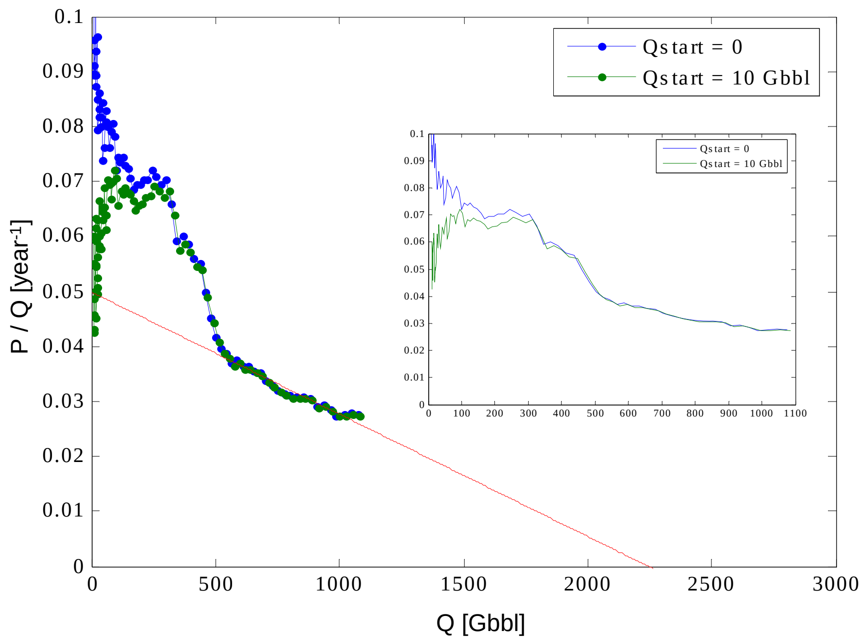

Figure III-6. Plot of relative world production rate (*P/Q*) against cumulative world production (*Q*) using two different starting values for cumulative world production in 1920, 0 and 10 Gbbl. The effect of assuming a relatively large, positive value for *Q*(1920) = Qstart has a significant impact on data points for small *Q*, but practically no impact on later data points. The major impact of variations in *Q* on early data points illustrate how these early data points are subject to much larger errors than later data points which "settle down." The same linear fit obtained in Figure III-4 is shown again for reference.

C. CRITICISMS OF THE HUBBERT METHOD

Optimists generally argue against the conclusions of Hubbertian peakists on more basic grounds than those just mentioned. Perhaps the most widespread criticism is that absolutely no economic factors are taken into explicit consideration in any part of the Hubbert model. Rather, the Hubbert model argues that physical scarcity alone, implied in the remaining fraction of URR (1–*Q*/URR), dominates long-term trends over economic factors such as price, demand, investment into production capacity, and level of technology available. Optimists cite a variety of examples of the economic conditions that have influenced oil production, such as the drop in production that followed the 1970s oil embargoes (see Figure III-3). This production drop is widely viewed to be the result of a contraction of demand over these years. An example of the influence of technology development on production capacity is the case of oil and gas production in the Forties field (UK, North Sea), whose production, according to Lynch, was predicted by Campbell in 1991 to decrease by 10% YoY but actually held steady and has declined only slightly on account of improved recovery technologies (Lynch 2004, Lynch 2003, Lynch 1997). To optimists the Hubbert analysis is far too simplistic—no model that completely ignores economic principles can possibly be useful for predicting oil production (Lynch 2004). In response, peakists generally argue that if the model were wrong it would not fit the historical data; the fact that it fits historical data (over a limited period) is evidence for its validity, and moreover, the best model is always the simplest one that can describe observations (Deffeyes 2005, p. 39). Peakists also point out that economic changes (demand, investment, and price changes), as well as technological developments, occurred throughout the time periods represented by data in Figures III-2 and III-4, but they maintain that such economic factors just do not matter very much in comparison to geologic scarcity (Deffeyes 2005, p. 39). The proof is said to be the ability of the model to explain historical data.

A second important criticism of the Hubbert approach is its assertion of and reliance on a fixed value for URR for all points in time. URR, optimists argue, is a number that grows with time as a result of the influence of improved technology and increased prices that make a larger fraction of the OOIP economically recoverable (IEA 2004, pp. 81–127; IEA 2005; Williams 2003; USGS 2000, Lynch 2004). Optimists cite the well-documented growth of proven reserves figures over history (see Figure III-7) and the well-known phenomenon of the growth of estimated reserves in individual reservoirs as evidence that URR should not be a static number in the Hubbert model. The basis of the optimist arguments seems to be that *there is no URR—or whatever it is, its value cannot be known with any fidelity whatsoever*. All that we know is that reserves have been grown in the past, and there is no reason to expect market forces will not ensure that this continues in the future.

Peakists, of course, disagree and fundamentally believe that URR is a meaningful quantity, even if our ability to estimate is open to some error. Further, they argue that much of the supposed growth in *reserves* (e.g., Figure III-7) is an artifact of antiquated and politically influenced methods of reporting reserves. As discussed in the beginning of this paper, URR, the ultimately recoverable *resource,* is a fundamentally different figure from the proven *reserves*. Reserves estimates are conservative figures whose values are often expected to grow, whereas URR figures attempt to make an accurate (not conservative) estimate of how much oil will ultimately be produced.

In spite of the disagreement over the use of reserves and resources, we decided to give optimists the benefit of the doubt and allow that URR resource estimates may grow over time, because the assumptions behind the estimates of URR are progressively made with higher and higher levels of technology in mind (Lynch and Adelman 1997). (We ignore the perspective that relatively little genuinely new technology has come down the research and development pipeline for at least a decade.) We tested the effect of a linearly increasing URR on the Hubbert model. Instead of a single value for URR in equations 1–3, we allowed URR to increase linearly from 2,250 Gbbl to various levels (2,500 Gbbl, 3,000 Gbbl, and 4,000 Gbbl) over the time period 2006 to 2100. The results and projected production are shown in Figures III-8–III-10.

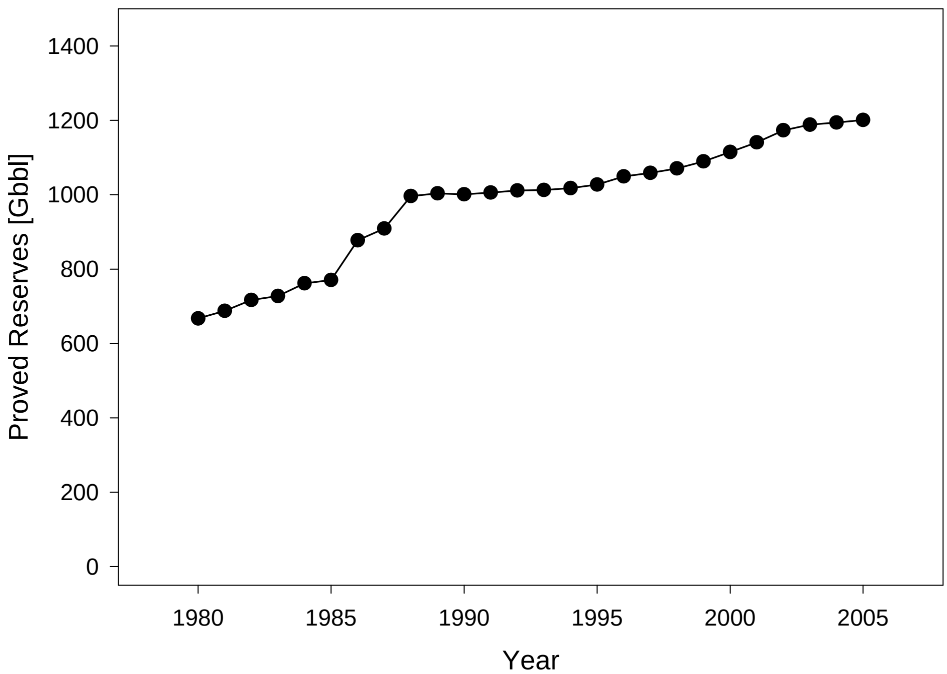

Figure III-7. Historical time series of global proved reserves as reported by *BP Statistical Review 2006* (BP 2006, pp. 1–48). The appreciation of the reserves is evident as the quantity nearly doubles over the 25-year period, despite high production levels.

The effect on the Hubbert model of allowing a linear increase in URR with time is to significantly extend the tail of the production over long periods of time. However, because this computational exercise set the URR in 2006 to the same level for all four projections, and because we also did not have URR increase at a rate greater than the growth of cumulative production, *Q*, *Q* overtakes a value of ½URR at about the same time for all four cases, and the timing of peak production is not shifted very much. Given that Figure II-2 indicated a range of current predictions of URR ranging from 2,000 to 4,000 Gbbl, a broader question might be, “What projections would the Hubbert method give using larger URR parameters that are constant for all times? These are shown in Figures III-11 and III-12 for URRs of 2,250, 2,500, 3,000, and 4,000 Gbbl.

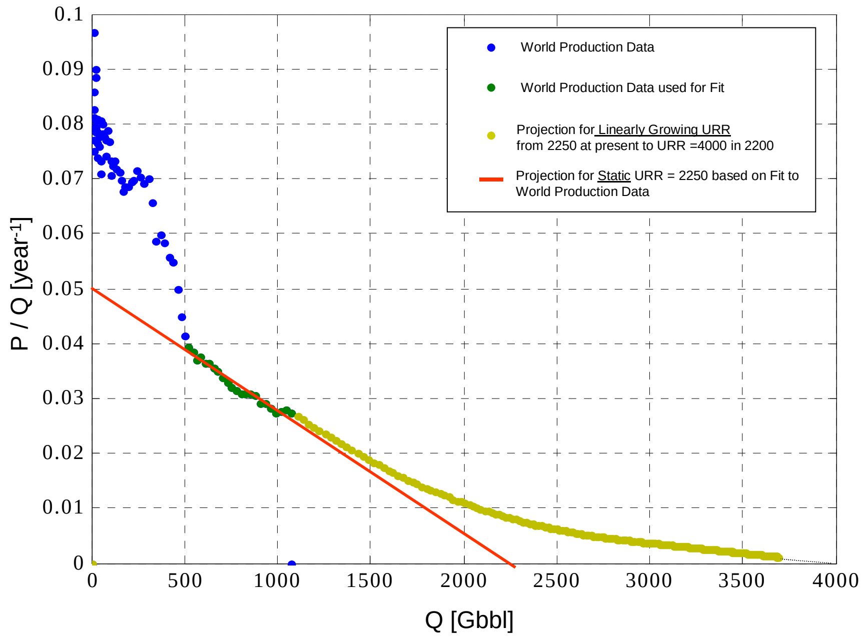

Figure III-8. *P/Q* versus *Q* plot for world production as in Figure III-4, showing the linear least squares minimization fit (red line) to the 1983–2005 data (green dots). Also shown is the projection obtained when URR is allowed to linearly increase each year from the initial fit value of 2,250 Gbbl in 2005 to 4,000 Gbbl in 2100. Instead of following a straight line as predicted by the basic Hubbert analysis, the curve asymptotically trends toward higher and higher values of URR

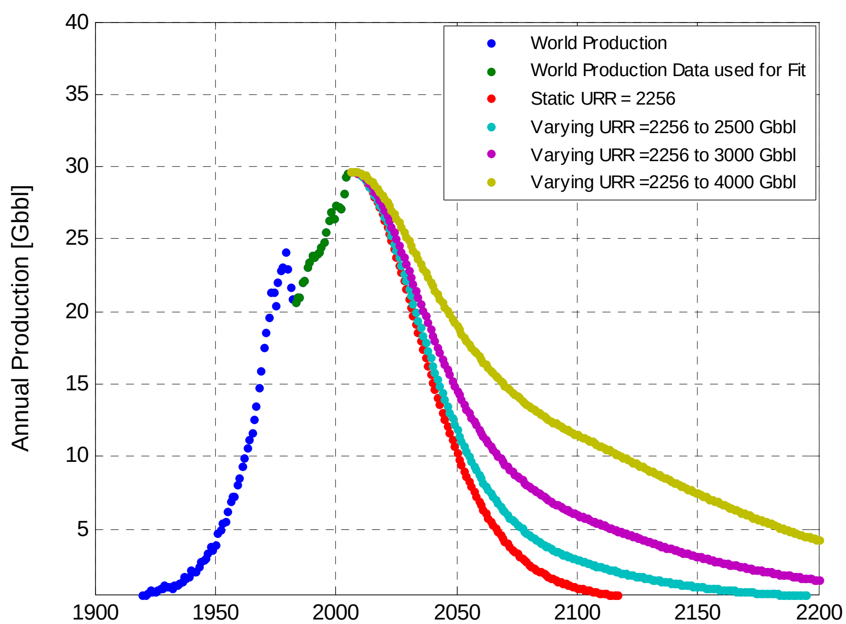

Figure III-9. Projections of world oil production for four different cases of linearly increasing URR, each beginning with 2,256 Gbbl (the URR obtained by fitting to historical data 1983–2005) in 2005 and increasing to: 2,256 Gbbl (red), 2,500 Gbbl (teal), 3,000 Gbbl (purple), and 4,000 Gbbl (yellow), respectively, in 2100.

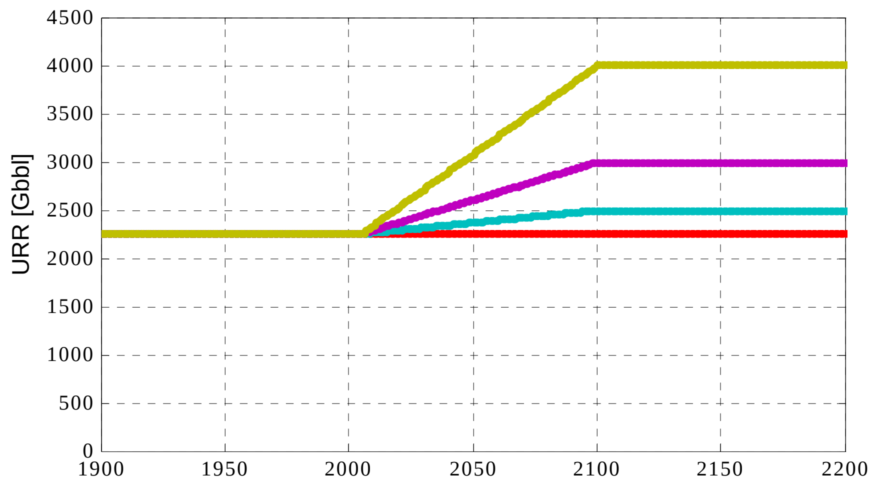

Figure III-10. URR values used for each year in the four cases of production projections shown in Figure III-9. Only data after 2005 are relevant to the projections

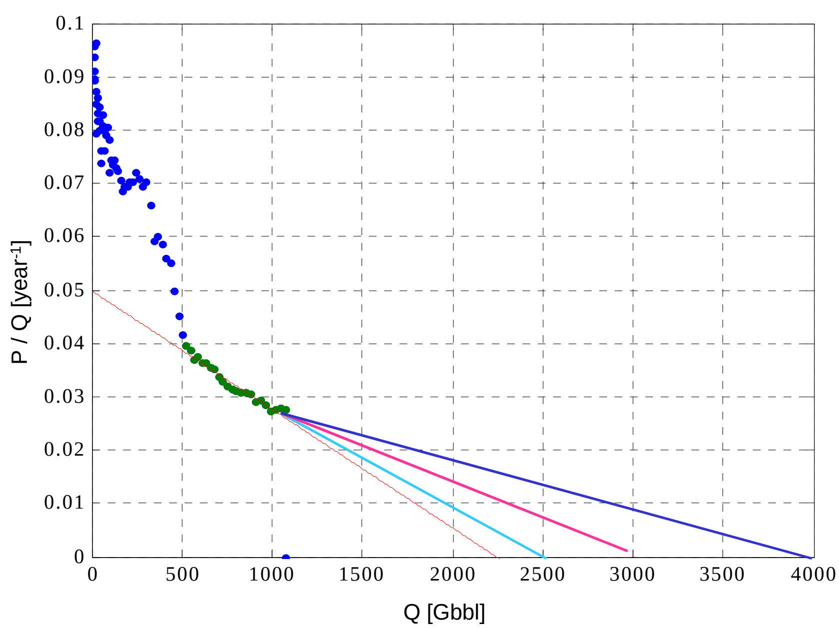

Figure III-11. *P/Q* versus *Q* plot for world production as in Figure III-4, showing the linear least squares minimization fit (red line) to the 1983–2005 data (green dots), which estimates URR to be 2,256 Gbbl. Also shown are the curves predicted by the Hubbert equation for three other *static* values of URR: 2,500 Gbbl (teal), 3,000 Gbbl (pink), and 4,000 Gbbl (dark blue). The difference between these projected curves and the projection shown in Figure III-8 is that here the same value of URR is used to project production in each year after 2005, whereas in Figure III-8, the production predicted in each subsequent used a different (increasing) value for URR.

We observe from these simulations that much higher peak production levels are obtained and the timing of the peak is shifted significantly, but not much more than 20 to

30 years (i.e., within a generation). Figure III-13 shows how the timing of the peak is shifted as different values of URR are used in the Hubbert model.

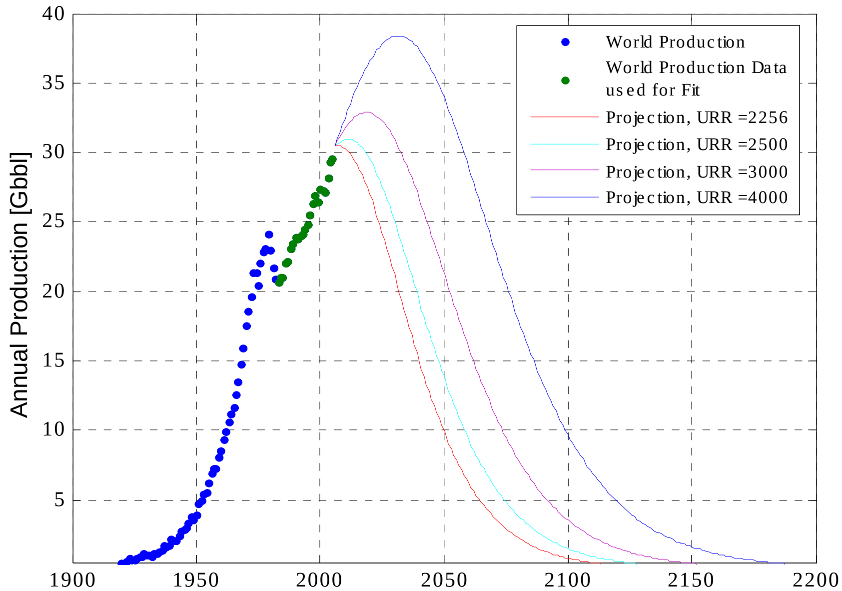

Figure III-12. Projections of world oil production based on the four curves shown in Figure III-11, which correspond to different (static) values of URR: 2,256 Gbbl (red), 2,500 Gbbl (teal), 3,000 Gbbl (pink), and 4,000 Gbbl (dark blue).

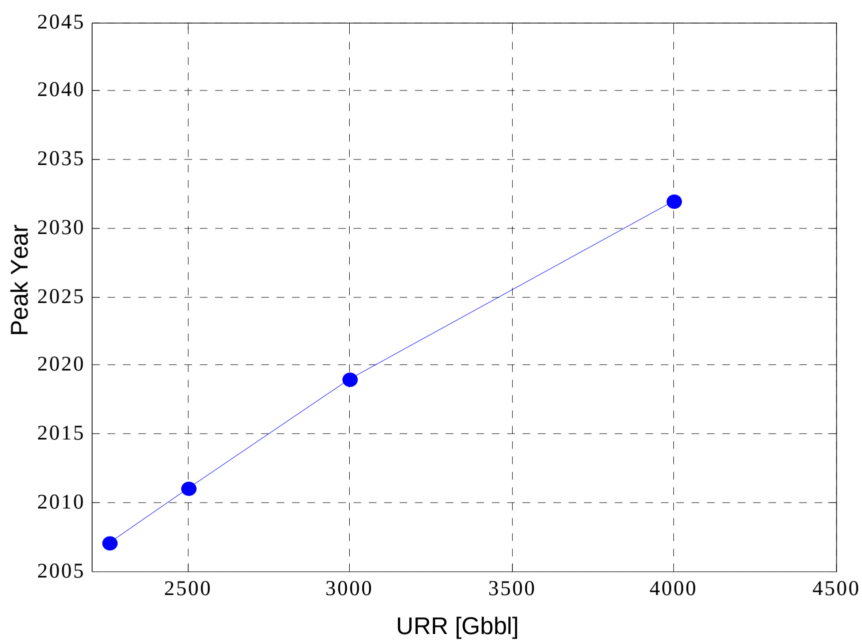

Figure III-13. Year of peak production based on projections in Figure III-12 versus the value of world URR used in those projections.

Besides criticism of the Hubbert method on the grounds that it naively ignores economic conditions and ignores possible URR growth via technology, etc., numerous other, less weighty criticisms are voiced by optimists. One criticism provided by M. Lynch is that when the production profiles of most major oil fields around the world in history are examined, only a small fraction (8 of 51) resembled the Hubbert (logistic) curve's symmetric rise, peak, and decline toward zero. According to this criticism, most production profiles are characterized by an asymmetric sharp rise and long tail, and many of the producing fields in the world in fact exhibit multiple peaks. These, argues Lynch, exemplify the oversimplification of the Hubbert analysis with its ignorance of economic information (Lynch 2004, Lynch 2003).

In our view this criticism seems superficial. The mere fact that individual oil fields do not show clean Hubbertian behavior does not imply that the sum of thousands of fields would not. In fact, because of their smaller size, they would be much more likely to be affected by factors that the Hubbert model considers minor and does not take into account (i.e., economics). In any case, as we showed for the example of time-varying URR, a simple modification of the basic Hubbert machinery can lead to an asymmetric production profile as in Figure III-9.

The Hubbert method is problematic, particularly the pre-1983 global production data. Nevertheless, its earlier success predicting the U.S. production peak and its current 25-year strong linear trend in global production (P/Q vs. Q) are compelling. On what basis might the projection of Figure III-4 (URR ~ 2,250 Gbbl) be believed?

D. GROUNDS FOR BUYING HUBBERTIAN PROJECTIONS: PHYSICAL OR EMPIRICAL BASIS?

Two elements of Hubbert's analysis are primarily responsible for suggesting the validity of its hypothesis (i.e., equation 1) and its projections into the future: first, the model explains (some) of the historical data, and second, the theory's physical argument seems intuitively sensible. Although these physical arguments are not well developed in most accounts of Hubbert's analysis, we can see at least two ways that production rate should be proportional to the fraction of URR remaining. First, on an individual reservoir basis, it is well known that the lower the fraction of URR remaining, the lower the production rate. As an extreme example, so-called stripper wells, which account for 25% of current (2003) U.S. production in the lower 48 states, produce on average about 2.18 bbl/well/day, as they pump out the very last fractions of URR remaining in these reservoirs (Moritis 2005). Contrast that figure with the thousands of barrels per day produced by new wells in many reservoirs. A second physical reason that the remaining fraction of global URR should limit production levels is that new reservoirs become harder and harder to find as more of the world's URR is used up. To demonstrate how equation 1 may describe the physical process of finding new reservoirs, Figure III-14 shows how the same approach can be employed to analyze historical discovery trends in the United States and the world.

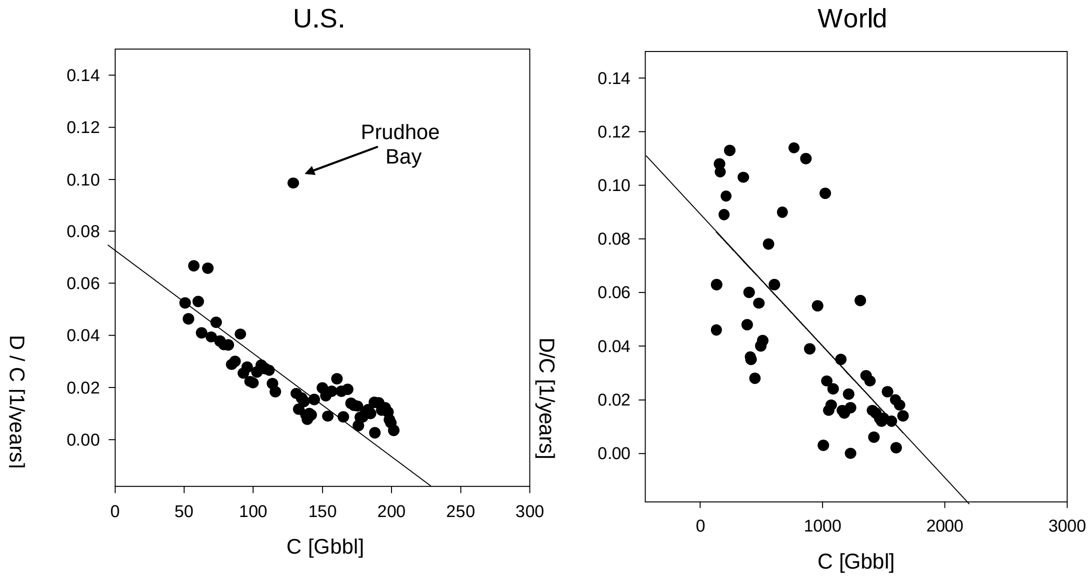

Figure III-14. Historical discovery trends for the United States and the world. In these plots D represents the volume of oil discovered in a single year, and C represents the cumulative amount of oil that has been discovered through that year, which is equal to cumulative production (*Q*) plus the reserves estimates for that year. Linear least squares minimization fits to the data are shown for each data set. Note that horizontal axis crossings are near the values of URR predicted by *P/Q* versus *Q* plots in Figures III-2 and III-4. Plotting D/C versus C attempts to illustrate how well the data follow a law given by equation 1 (substituting *P/Q* and D/C). A good fit to the law provides support for the physical basis of the law, which says that production becomes more difficult as the remaining fraction of oil decreases because the discoveries become more difficult as the remaining number of fields/reservoirs decreases. U.S. discovery data was obtained from *Oil and Gas Journal* for the years 1946 through 2005 (Oil and Gas Journal 2006a), where D was calculated as "new field discoveries" plus "new reservoirs in old fields" plus "reserve regions" (growth), and C was calculated as cumulative production plus net changes in reserves. World discovery data plot is based directly on a data plot published by Deffeyes (Deffeyes 2005, p. 46).

In this analysis D represents the total discovered oil in a year, including changes to reserve estimates, and C represents the cumulative discovered oil—total reserve estimates plus cumulative production (*Q*)—for that year. D is like the runs scored by a baseball team in an inning, while C is the total scored by the team thus far in the game. Again, the data for the United States are significantly cleaner than those for the world total, but both data sets are scattered enough that any results drawn from them should be met with a measure of skepticism. Nevertheless, peakists point out that linear fits of these data result in crossings of the C axis—the total cumulative oil expected to be discovered—that are very near the predictions of URR by the *P/Q* v. *Q* plots shown earlier (Figures III-2 and III-4): 230 Gbbl for the U.S. and around 2,250 Gbbl for the world. By presenting the discovery data plotted in this way along with the earlier production (*P/Q* v. *Q*) plots, peakists imply that the Hubbert analysis represents a physical basis for limitations on oil production.

Under more careful consideration, however, the appealing physical grounds for the Hubbert theory's validity seem inconsistent with that production figure that the equation supposedly describes. If equation 1 is true on physical grounds, then the production rate that it calculates must be a production *capacity*—that is, how much it is *possible* to produce, not how much is *actually* produced. Indeed, the explanations of the Hubbert method employed by peakists treat the hypothesis in exactly this manner: "that equation says that our *ability* to produce, *P*, is linearly dependent on the fraction of oil that remains" (our italics) (Deffeyes 2005, p. 39). The implication of this understanding of the hypothesis, equation 1, coupled with the fact that the equation fits (some) historical data, is that *historical data represent production at capacity*. Possibly this is the case for the segments of data that fit a straight line well in Figure III-4, while periods of production data that do not fall on the straight line of Figure III-4 represent deviation from production at capacity. Even if this is true, the Hubbert model only captures part of the story and is not satisfactory to predict when and to what effect economic considerations would lead to production beneath capacity.

To gain some insight into how economic factors might alter the Hubbert predictions, we performed the same analysis presented earlier (Figures III-11–III-13), but this time with a 0.5% ceiling on the year-on-year (YoY) growth in production for all years after 2006. Such a limit on production growth might be caused, for instance, by limited increases in demand for oil. Since IEA estimates of demand growth over the coming 3 decades is about 2%, we took a YoY production growth limit of 0.5% to be a minimal growth (and maximum delay of the Hubbert peak) scenario. Figures III-14–III-17 show the results of such projections.

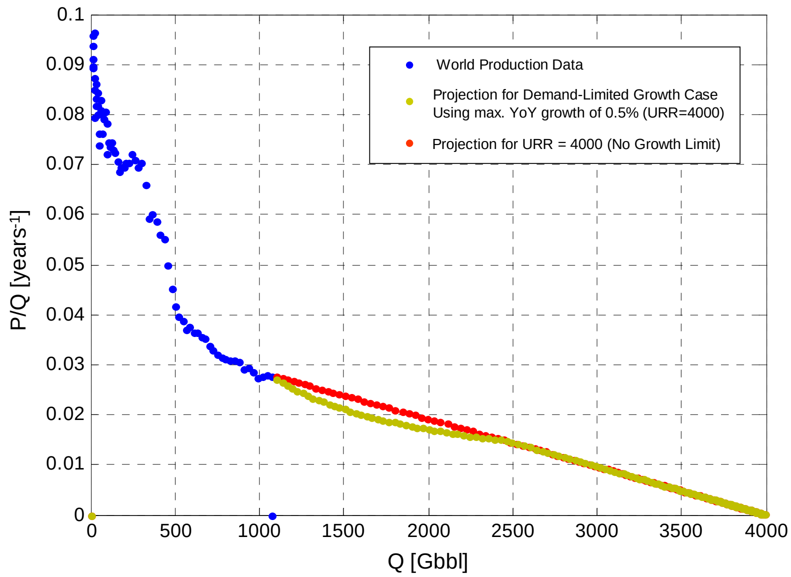

Figure III-15. *P/Q* versus *Q* plot for world production showing two projections. The first (red dots) is the projected curve based on the basic Hubbert model with a (static) URR value of 4,000 Gbbl. The second (yellow dots) is the curve projected using the Hubbert equation 1 and same URR (4,000 Gbbl) but imposing a limit on YoY production growth based on limited demand growth of 0.5%. For these demand-limited projections, whenever the Hubbert equation predicts a production increase that is greater than 0.5% YoY, the actual prediction used is limited to the 0.5% ceiling value, and the cumulative production is adjusted accordingly.

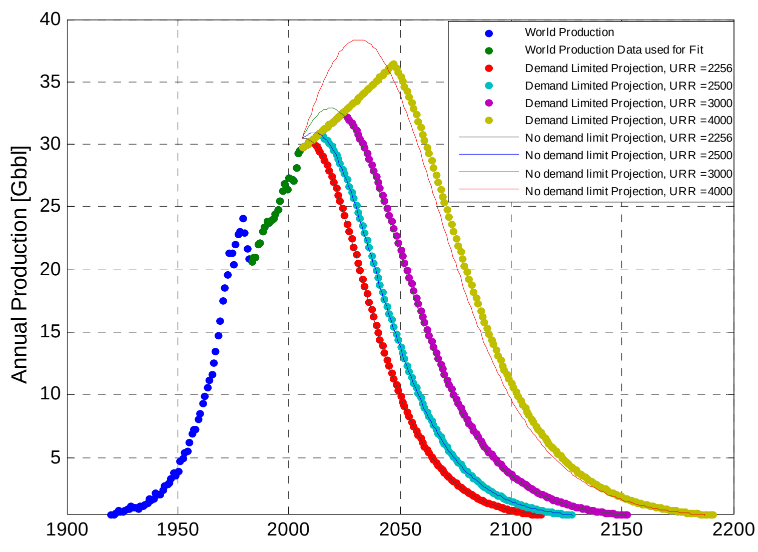

Figure III-16. Comparison of Hubbert method based on world oil production projections for the case of demand-limited production growth (red, teal, purple, and yellow dots; 0.5% YoY growth limit as described in Figure III-16) and the case of no growth limit (brown, blue, green, and red lines; same data as Figure III-12). The comparison between the "with-demand-limit" projection and the "no-demand limit" projection is made for four different assumed values of URR: 2,256 Gbbl (brown line, red dots); 2,500 Gbbl (blue line, teal dots); 3,000 Gbbl (green line, purple dots); 4,000 Gbbl (red line, yellow dots).

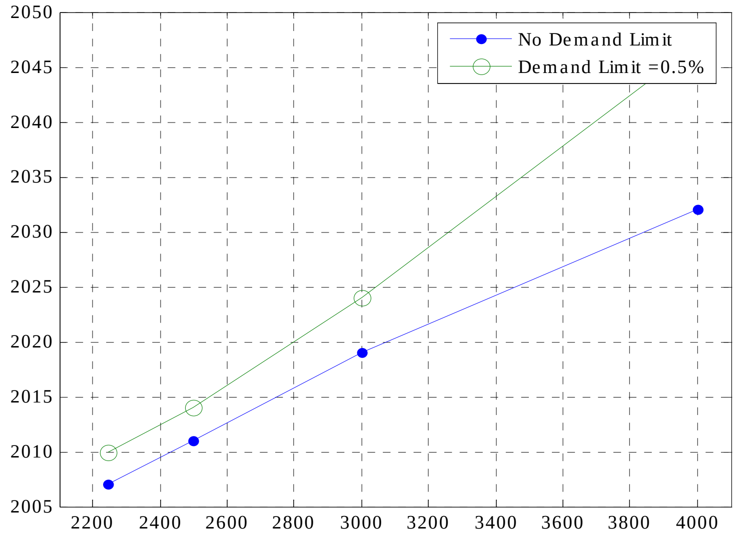

Figure III-17. Comparison of projected peak years versus URR for the two different methods compared in Figure III-17—"with-demand-limit" and "no-demand-limit."

The effect of a ceiling on production growth on the *P/Q* v. *Q* plot in Figure III-15 is to push data points below the straight line they would otherwise follow in the basic Hubbert model, consequently slowing the march of *Q* toward URR. The resulting projections of production over time are shown in Figure III-16 for four different (static) values of URR and, for comparison, are plotted along with the earlier results (from Figure III-13) that had no limit on growth. Imposing a limit on production growth significantly delays the timing of a peak, but not overwhelmingly (Figure III-17). This analysis shows how economic considerations might be appended to the core Hubbert analysis, if we understand the hypothesis (equation 1) to represent a physically derived expression for production at *capacity*.

If, on the other hand, we dispense with the physical grounds for equation 1 and understand world historical production data not to represent production at capacity,[3] but rather production at a level dictated by supply and demand (but beneath a physically determined ceiling), then any success that equation 1 has at modeling real data must be understood as an empirical law, not one motivated a priori by physical principles. We are

3 One reason that world historical production data are not viewed as production at capacity is the long list of examples of economic and political instruments that limit production to maintain price stability. Well known instances include OPEC quotas set over the past 20–30 years aimed at holding the price of oil inside of an agreed range (e.g., $20–30 /bbl) (Simmons 2005, p. 85) and the rationing of oil deliveries by the Texas Railroad Commission until 1972 (Deffeyes 2005, p. 44).

left with an equation 1 that somewhat fortuitously describes production levels over specific time periods. The problem with making predictions on this basis is that we lack a detailed understanding of why such an empirical equation has worked on certain time domains of data, and hence we do not understand what (economic) conditions and assumptions must remain true to know for certain that the empirical trend will hold into the future. Work in this area is in progress, however. Kaufmann et al. have argued that because the pure Hubbert analysis omits economic factors, no small measure of "luck" was required for Hubbert's prediction of the U.S. lower-48 production peak to be correct (e.g., the unchanged rationing policies of the Texas railroad commission). Kaufmann et al. consider $P = dQ/dt$ of equation 1 to represent actual production (not capacity) and introduce refinements of the Hubbert equation to account for economic influences (Kaufmann 2004).

IV. DECREASING DISCOVERIES WARN OF PEAK OIL

The previous section explained in some detail the basic arguments behind assertions of an imminent oil production peak based on the Hubbert analysis. Other analyses warn of an impending peak, however. Most of these arguments are based on either technical observations about the nature of oil reservoirs or declining discoveries. This section will highlight some of these arguments and their counterarguments.

A. DECLINING DISCOVERIES SIGNAL APPROACHING PRODUCTION PEAK

The cornerstone of most arguments that do not explicitly use the Hubbert method is the observation that discoveries of oil appear to be in the midst of a decades-long decline. Peakists argue that most of the world is heavily explored, save for Arctic and extreme deepwater regions, and that it is therefore unreasonable to expect any upturn in the trend. Figure IV-1 presents backdated[4] discovery data compiled by Laherrere and Campbell based on a proprietary database (IHS Consultants), which shows an overall peak in discoveries during the 1960s and a more or less relentless decline in the 40 years since then.

Peakists argue that the peak in world discoveries seen in the Figure IV-1 is a harbinger for the oncoming peak in world production. Because one must first find oil before it is produced, they argue, the production profile should approximate the discovery profile when it is shifted in time by about 35 years.[5] Figure IV-2 shows how this analysis gives a good correlation for U.S. production and discovery.

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4 The discoveries presented in this figure are backdated, which means that all reserves and cumulative production from a field (i.e., C from Figure III-15) are assigned to the year that that field was discovered. This means that all subsequent reserves growth for a field discovered in 1948 are assigned to the year 1948**.**

5 Laherrere admits that a simple time-shift of the discovery profile only works to predict unconstrained production. If production is constrained in any way by political or economic factors, then the temporal shift may be inconsistent, and the match between discovery and production will not be as good. This is offered as an explanation for why the data for “swing producers” (who limit production to stabilize prices, e.g., Saudi Arabia) do not work as well in this analysis (Laherrere 2001, pp. 1–27).

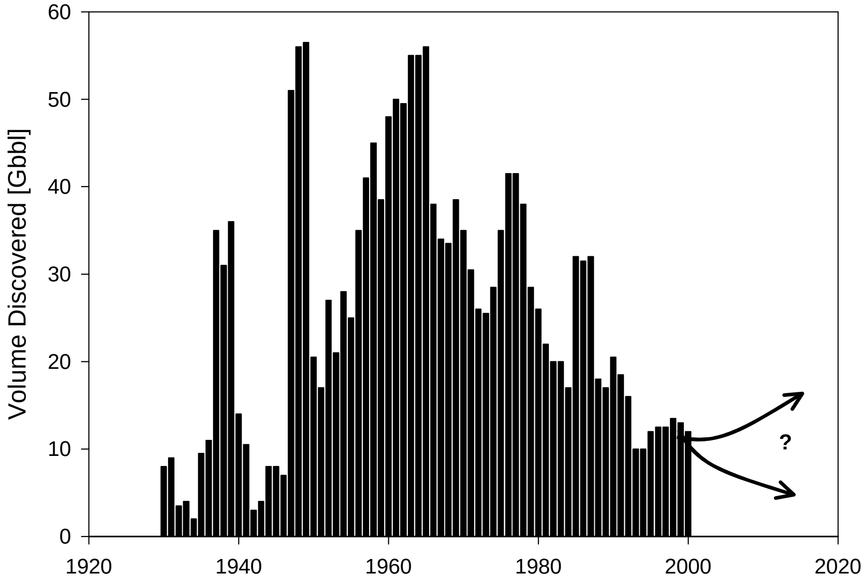

Figure IV-1. Annual volume of oil discovered in the entire world by year. These data, originally published by Campbell (2003), are backdated as described in the text here based on the explanation of Laherrere (2001).

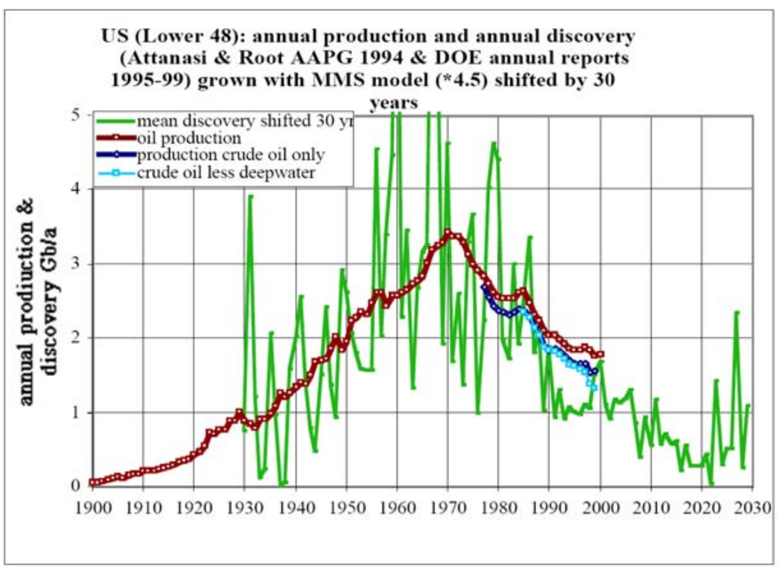

Figure IV-2. Correlation between U.S. discovery profile (green) and U.S. production profile (red) as presented by Laherrere (2001).

In addition to the apparently inexorable decrease in the annual volume of oil discovered, the average size of discoveries has been decreasing substantially over the past 40–50 years as shown by Figures IV-3 and IV-4.

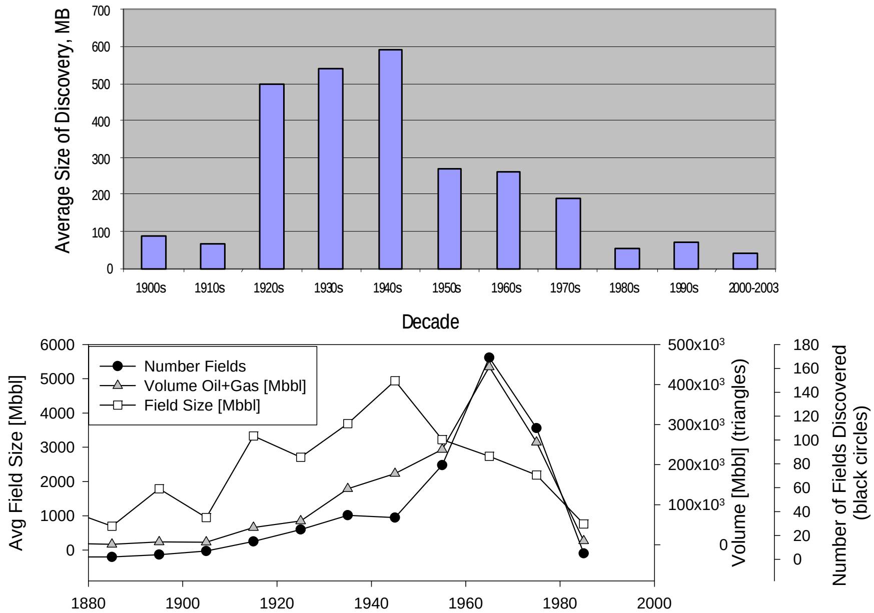

Figure IV-3. (Top): Mean size of new field discovery for entire world by year. (Source: Vassiliou 2006). (Bottom): Temporal distribution of discoveries for the largest 509 fields discovered through 1984. The average field size for the giant fields approximately tracks the overall (all fields) average size in the top graph, which peaked in the 1940s. The actual number of (giant) fields and the volume of oil in these discoveries peaked in the 1960s, however, corroborating the shift of recent discoveries to smaller fields. We understand these figures to be backdated, meaning that more recent discoveries have had less time for growth. (Source: Carmalt and St. John 1984, pp. 11–40).

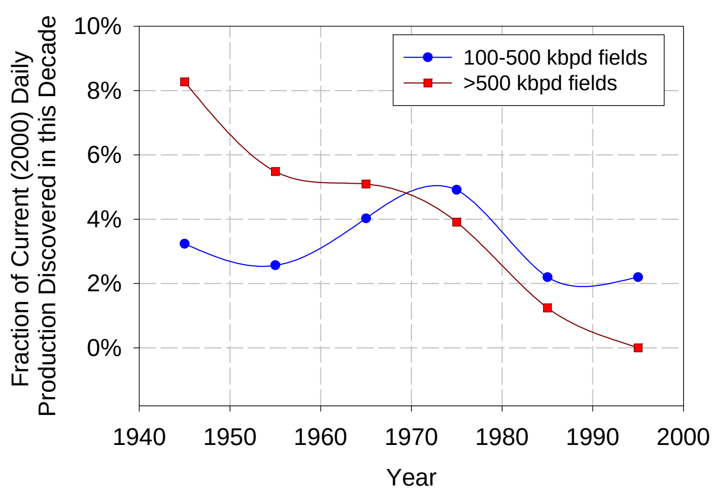

Figure IV-4. Fraction of year 2000 production that originated from fields of two size categories (>500 kbpd, 100–500 kbpd) according to the decade in which the fields were discovered. While it is to be expected that very recent discoveries would contribute only a small fraction of production in the year 2000 since time is required to bring new discoveries into production, the downward trend of large field contributions compared with smaller fields illustrates that degree to which the subset of discoveries that provide our current (year 2000) production have shifted from large field discoveries to small field discoveries over the past 60 years. Source Data: Simmons 2005, p. 375.

The trends indicated by these plots are consistent with the fact that oil fields and reservoirs are obviously not distributed evenly by size—there are thousands of times more small reservoirs and fields than there are giants, as indicated by the distribution of field sizes given in Figure IV-5. The distributions of size given in Figure IV-5, of course, may not represent the distribution of what will ultimately be found, but they represent how the fields that humans have managed to find so far are distributed in size, which is a strong indication for the future. In fact, if experience within individual field basins is any indicator, the distributions of field sizes should be even more heavily weighted toward small fields than those in Figure IV-5, meaning that the undiscovered remainder would be composed mostly of small fields.

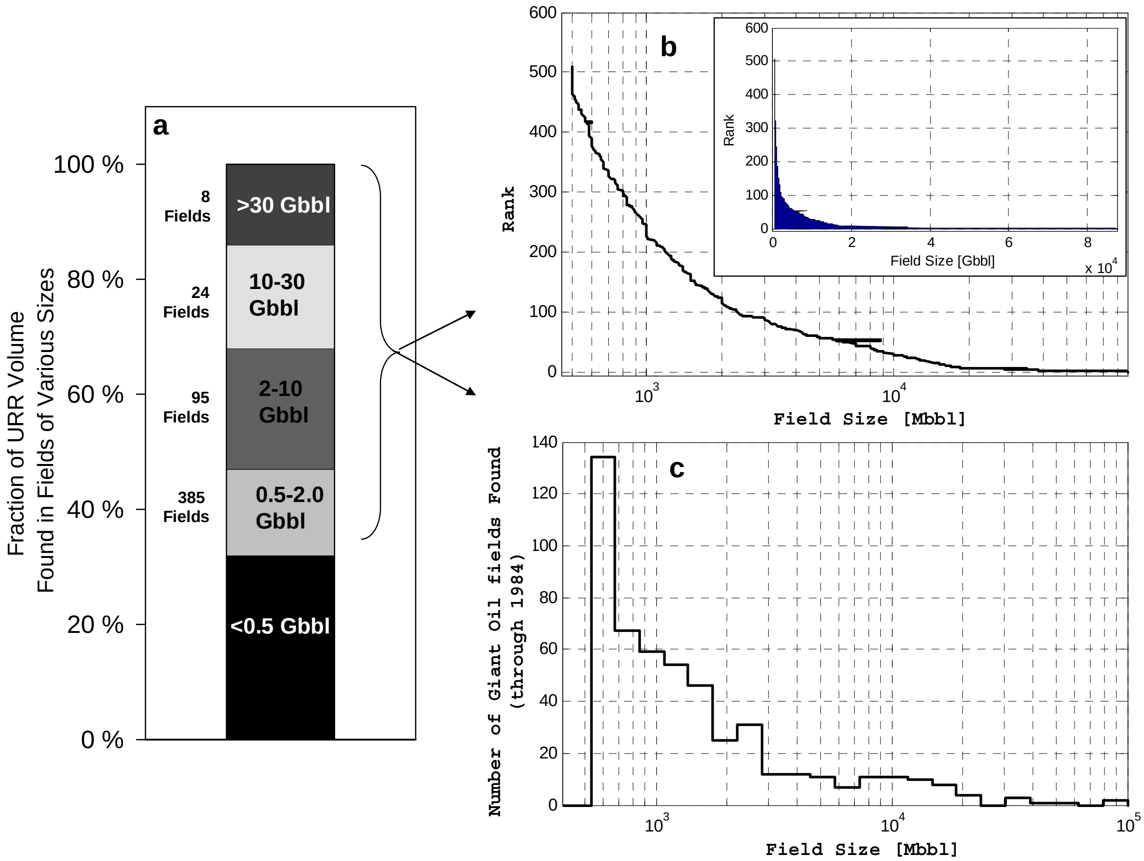

Figure IV-5. World oil field size distributions. (a): Distribution of oil reserve volumes over various field sizes. Only 512 fields account for over 2/3 of reserves. (Source: Vassiliou 2006). (b): Field sizes, ordered by rank, of the largest 509 fields in the world as estimated in 1984; note that the main plot uses a log-scale for field sizes; the inset plot spaces the field sizes linearly. (c): Histogram of the data from plot b shows the distribution of field sizes plotted on a log-scale for the largest 509 fields in 1984. These plots emphasize the extreme rarity of supergiant fields like Ghawar in Saudi Arabia. (Source for plots b and c: Carmalt and St. John 1984 pp. 11–40).

Simmons explains that oil exploration within basins follows a predictable pattern, one

> described by [scientists] at the French Petroleum Institute (IFP) as the "King, Queen, and Lords of an oil basin." Based on a review of all known oil fields, the IFP study revealed that any petroleum basin, regardless of its extent, contains oil fields of various sizes that can be ranked in a predictable hierarchy: one king, 1–3 queens; 5–10 earls or lords; a large number of commoners (Simmons 2005, p. 127).

The trends shown in Figures IV-3 and IV-4 indicate that in general, the kings and queens of the world have mostly been found, which means that the remaining conventional oil is distributed over these numerous tiny fields. In this view, the future of world oil production looks more like current U.S. operations, with 511,440 wells producing about 5 Mbpd, and not like Saudi Arabia's current operations, which produce over 10 Mbpd using only 1,560 wells (natural gas liquids not included) (BP 2006, pp. 1–48; Oil and Gas Journal 2006a; Oil and Gas Journal 2006b). The consequence of the remaining oil being in more distributed smaller fields is said to be higher costs and greater difficulty in producing the remaining reserves.

B. ECONOMICS AND PROPER ACCOUNTING MAY DISCREDIT CONCERNS OVER DISCOVERY DECLINE

A number of important criticisms of the foregoing analyses have been made by optimists, the first being to question the method of backdating discovery figures (Figure IV-1). By assigning all the oil discovered in a particular field, *plus all the reserves growth that has occurred since,* to the field's year of discovery, older field discoveries are disproportionately inflated compared to newer fields. Lynch contends that backdating discoveries in this way is a fallacy analogous to planting trees over 20 years, observing that the average size of the most recently planted trees is small compared to older ones, and then concluding that timber resources would soon become scarce (Lynch 2006, pp. 1–32). We attempted to roughly "correct" the backdating of discoveries in Figure IV-1 based on the growth function that Laherrere reports using for backdating of U.S. discoveries (Laherrere 2001, pp. 1–27),

$$URR(t) = \left(1 + 0.07(t - t_o)\right) \times URR(t_o), \tag{4}$$

where t_o is the year of discovery, $URR(t_o)$ is the initial estimate of the oil in the field, and $URR(t)$ is the appreciated estimate of the oil in the field in year t. The result of this "discounting" procedure should approximate the volume of oil found each year in terms of the initial estimates of the reserves made at the time of discovery, that is, $URR(t_o)$. The results, shown in Figure IV-6, significantly mitigate the historical decrease in discovery volumes. Because the method used in this analysis is so simplistic and rough, however, an improved effort should be made before drawing any final conclusions about discovery trends.

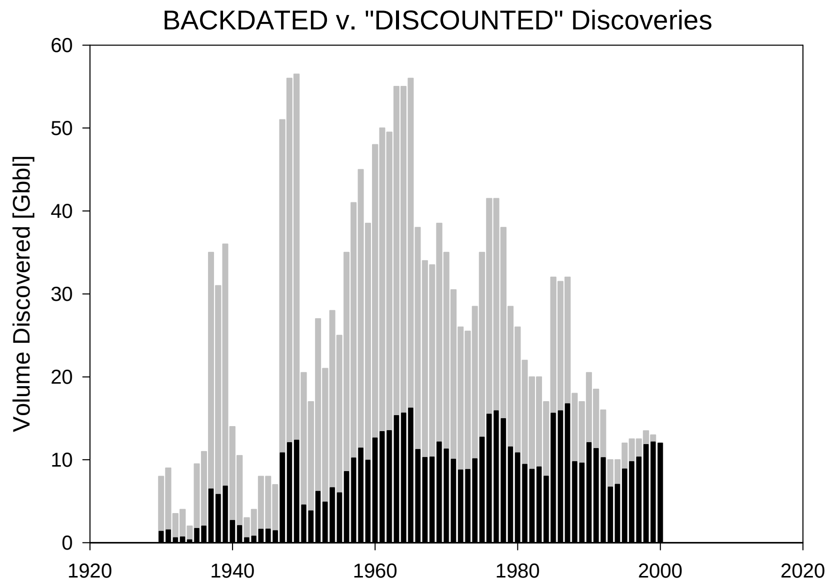

Figure IV-6. Comparison of backdated and "discounted" annual volumes of oil discovered in the entire world by year. The backdated data (gray) are the same data presented in Figure IV-1. The "discounted" discoveries data (black) were derived from the same data, but the volume of oil assigned to each year was reduced by a factor described in the text that accounts for the amount of field growth expected between the year of discovery and the year 2000. Dividing by this factor attempts to remove the volumes of oil that are assigned to that year that resulted from subsequent field growth. As such the discounted data approximate the volume of oil found each year as it was originally estimated. Sources: data: Laherrere (2001), discount factor: MMS model (Laherrere 2001, pp. 1–27)

More fundamental than reserves growth, however, is the optimist argument that any decline in discoveries is not an indication of dwindling supply, but rather a reflection of the fact that exploration efforts have been comparatively low over the past few decades, especially in some of the important oil-producing regions of the world, like the Middle East. Of the exploration that did occur over the past few decades, they point out, most happened in non-OPEC countries and in regions known to be mature. Thus, optimists believe large areas of the world remain to be explored, and they see no evidence of a declining ability to find oil, only a decrease in exploration effort. In support of this view, optimists point out that drilling success rates, that is, the percent fraction of wells drilled that yielded producible oil, show steady increases over the same period of history (see Figure IV-7).

Any decline in discoveries over the past few decades is easy to explain, say optimists, when the economic conditions that prevailed over that period are considered—low oil prices and high reserves-to-production (R/P) ratios. Low oil prices provide less money for industry to invest in exploration efforts, and high R/P ratios provide no incentive to find more reserves. To explore for oil that will not be needed for another 40 years would be economically irrational. Furthermore, optimists argue that despite decreases in new discoveries, reserves growth in already-discovered fields have been more than sufficient to make up the difference and maintain a slightly increasing R/P ratio for the world over the past 25 years, as shown in Figure IV-8. In other words, all the concerns that peakists raise can be explained when economics are taken into consideration.

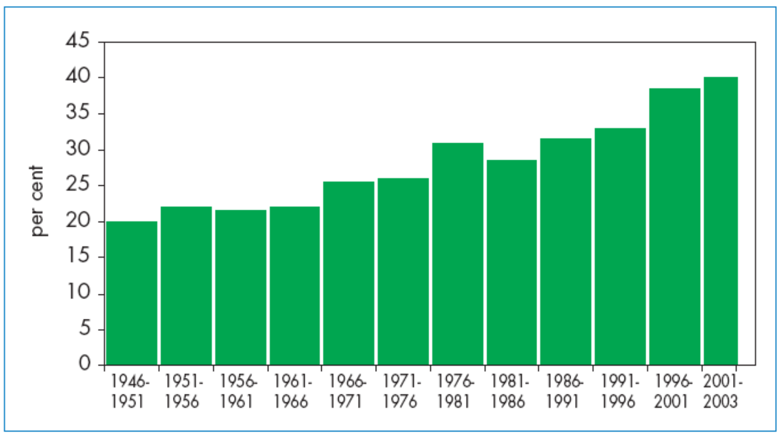

Figure IV-7. World oil exploration drilling success rate as reported by the IEA (original source IHS Energy) (IEA 2004). These figures represent a numerical success rate (i.e., the number of exploration wells that yielded any producible oil per exploratory well drilled) rather than the volumetric success rate (i.e., the volume of oil found per exploratory well drilled).

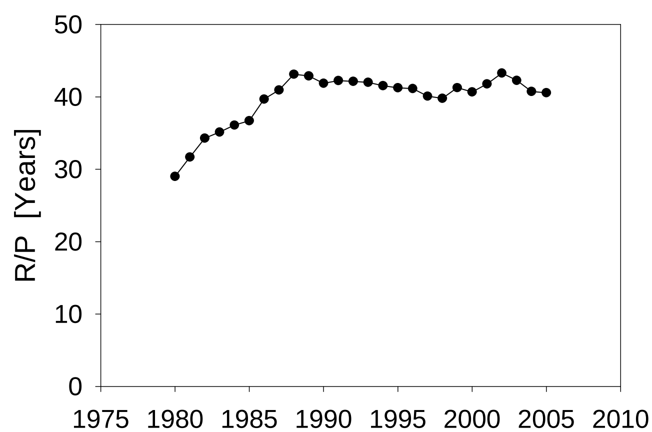

Figure IV-8. Global R/P ratio based on world proven reserves and production of crude oil plus natural gas liquids as reported by *BP Statistical Review 2006* (BP 2006, pp. 1–48).

C. OPTIMIST RETORT: EXPLORATION EFFORT IS HIGH, AND R/P RATIOS DO NOT DISPROVE PEAK

Or can they? Figure IV-9, taken from the IEA's *World Energy Outlook 2004,* shows a so-called creaming curve for world oil exploration since 1963 (a wildcat is a well drilled in a location not previously known to contain oil). From this figure two facts can be deduced. First, the global average rate of drilling wildcats increased in the period since 1980 compared with the 17 years previous: only about 900 wildcats per year were drilled on average from 1963 to 1980, but about 2,600 were drilled per year on average between 1980 and 2002—a 180% increase. Second, from Figure IV-9 we conclude that only about 16 Mbbl were discovered per wildcat drilled since 1980 compared with about 100 Mbbl per wildcat for the period 1963 to 1980. The volumetric success rate appears to have gone down significantly.[6] A very similar figure was offered by Laherrere for just the Middle East: the first 1920 wildcats in the Middle East yielded 723 Gbbl (by 1980) while the next 1,760 wildcats in the Middle East have yielded only 32 Gbbl (since 1980) (Lynch 2003). Reserves growth aside, these figures suggest that exploration efforts have in fact been very significant and perhaps increasing—a very different story from that of the optimists.

Two factors might account for some of the discrepancy between these figures and the optimist's view that low exploration effort is cause for low discoveries. First, it is not clear whether or not the discovery data in Figure IV-9 are backdated. If the data are backdated, then in addition to the oil discovered at the time of a given wildcat, *all oil subsequently found and developed at that wildcat* would be assigned to the year of the original wildcat discovery. We believe that these data are not backdated, however, because they originated from the IEA, whose views coincide mostly with those of the optimists. The figures quoted from Laherrere may in fact be backdated, so reserves growth could close some of the apparent differences in exploration success in the Middle East pre- and post-1980. More important, though, according to optimists, much of the exploration that has occurred post 1980 was in mature areas of the world, and in the case of Laherrere's figure, in mature, well-developed areas of the Middle East that stand a low likelihood of yielding discoveries. This fact, optimists would contend, is the reason for

6 Note that the decline is in volume, as opposed to the *number* fraction of successful wells, which has increased since 1980, as reported in Figure IV-7.

the decreased yield on exploration in recent times. At this time, we cannot verify or refute this claim.

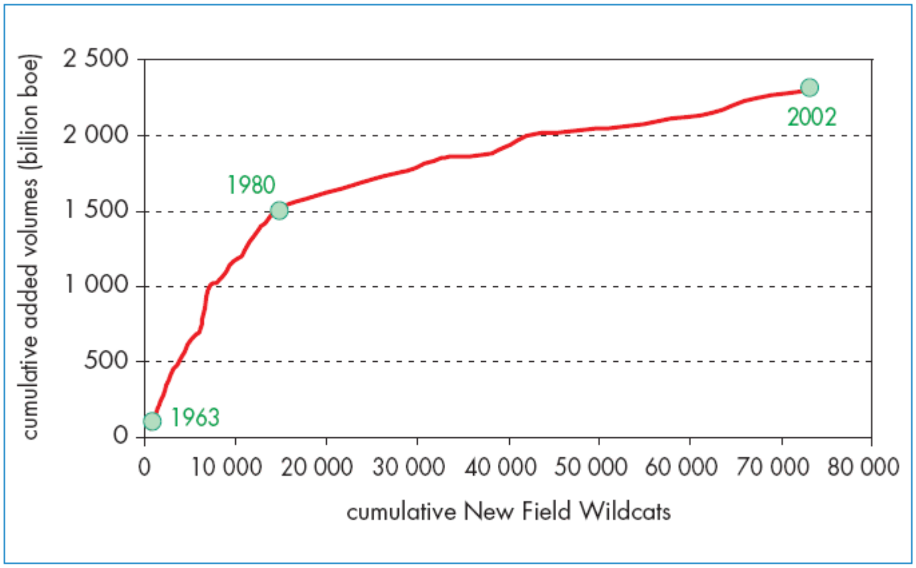

Figure IV-9. So-called creaming curve of world exploration since 1963 as reported by IEA (IEA 2004, pp. 81–127). These data include both oil and gas exploration and show not only the amount of oil found per wildcat drilled (the volumetric success rate), but also shows changes in the average temporal rate at which new wildcats were drilled for the periods 1963–1980 and 1980–2002, thus showing the relative exploration effort that occurred during those periods.

Apart from these discovery-based arguments, peakists may call into question whether the high R/P ratios quoted by optimists are relevant. As discussed in the beginning of this paper, the proven reserves figures (used to calculate R/P) reported by countries and companies may be heavily influenced by nontechnical factors, and therefore the reserves figures, and the supposedly high R/P ratios, should not be trusted. A specific, well-known example of this is shown in Figure IV-10. Over the course of a few years in the 1980s, the reported reserves of a handful of OPEC nations suddenly spiked by factors of over 100% in many cases, even though no new discoveries were reported. Furthermore, the reported reserves of many of these nations have remained practically flat since then, despite billions of barrels of production and few major discoveries.

Although the nations involved have not provided official explanations for the anomalous jumps in the 1980s, the reason is widely suspected to be a response to the OPEC policy under consideration during that period, which would tie each nation's oil export quota to the amount of reserves that it has (Williams 2003). If these suspicions are valid, then there is strong cause to believe that the world’s proven reserves are overstated substantially.

HOW OPEC OIL RESERVES SPIKED — Table 1

	Abu Dhabi	Dubai	Iran	Iraq	Kuwait	Neutral Zone	Saudi Arabia	Venezuela
1980	28	1.4	58	31	65	6.1	163	18
1981	29	1.4	58	30	66	6.0	165	18
1982	31	1.4	57	30	65	5.9	165	20
1983	31	1.4	55	41	64	5.7	162	22
1984	30	1.4	51	43	64	5.6	166	25
1985	31	1.4	49	45	90	5.5	169	26
1986	30	1.4	48	44	90	5.4	169	26
1987	31	1.4	49	47	92	5.3	167	25
1988	92	4.0	93	100	92	5.2	167	56
1989	92	4.0	93	100	92	5.0	170	58
1990	92	4.0	93	100	92	5.0	258	59
1991	92	4.0	93	100	95	5.0	258	59
1992	92	4.0	93	100	94	5.0	258	63
1993	92	4.0	93	100	94	5.0	259	63
1994	92	4.0	89	100	94	5.0	259	65
1995	92	4.0	88	100	94	5.0	259	65
1996	92	4.0	93	112	94	5.0	259	65
1997	92	4.0	93	113	94	5.0	259	72
1998	92	4.0	90	113	94	5.0	259	73
1999	92	4.0	90	113	94	5.0	261	73
2000	92	4.0	90	113	94	5.0	259	78
2001	92	4.0	90	113	94	5.0	259	78
2002	92	4.0	90	113	94	5.0	259	78

Source: OGJ

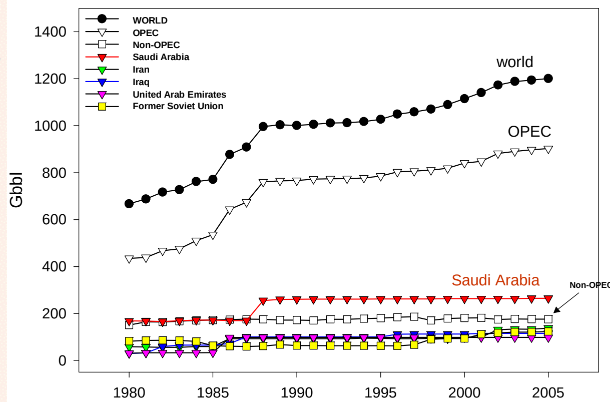

Figure IV-10. Anomalous, unexplained spike in proven reserves figures reported by OPEC nations during the 1980s. The data table on the left was taken from *Oil and Gas Journal* (Williams 2003), and the data plot on the right is based on data from the *BP Statistical Review 2006* (BP 2006, pp. 1–48).

Finally, note that just because R/P is steady at constant value, it does not mean that production cannot peak and decline. Having a large R/P only means that a country has found, but not yet produced, a lot of oil compared with current production. If discovery leads production by about 35 years as Laherrere claims (Laherrere 2001, pp. 1–27), then we would expect R/P to be over 30 years at the production peak of 32 Gbbl/year for a URR of 3,000 Gbbl. Figure IV-11 shows that R/P gave no indication of the production peak that actually occurred in the U.S. in the early 1970s. For these reasons we believe that appealing to R/P ratios as evidence against a possible impending peak is misleading.

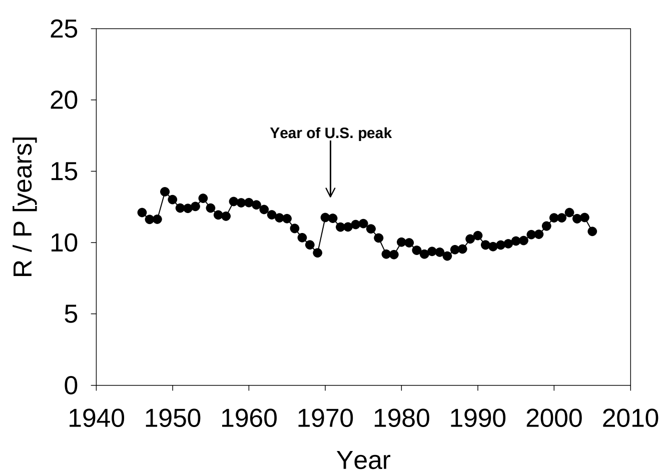

Figure IV-11. U.S. R/P ratio based on world proven reserves and production of crude oil based on *Oil and Gas Journal* Data (Oil and Gas Journal 2006a).

D. TECHNICAL CONCERNS OVER SAUDI PRODUCTION CAPACITY: A HARBINGER OF PEAK OIL?

Rounding out the peak oil debate are technical arguments concerning Saudi Arabian production in the near term (i.e., next 10 years) made prominent by M. Simmons among others. Whereas the foregoing peak-oil analyses took a broad view of world oil production to predict when a production peak might occur, Simmons focuses on technical indications that Saudi Arabia's production rates can no longer grow with demand: "[P]eaking does not mean running out of oil. It means that supply no longer can grow and it generally means the pending arrival of a production decline."

Simmons's core argument begins by pointing out how vital Saudi Arabia is to world oil supply. Saudi Arabia currently provides 13.5% of world oil production (nearly half of Middle East OPEC production) (BP 2006, pp. 1–48), and the IEA expects Middle Eastern oil to contribute 75% of projected growth in world production capacity over the next 20 years, as world production approaches 120 Mbpd in 2030 (IEA 2004, pp. 81–127). This would correspond to Saudi Arabia increasing its production from about 10 Mbpd currently to 20 Mbpd over the next 30 years if it is to maintain approximately the same market share.[7] Simmons then observes that Saudi Arabian oil production depends on the output of only a few (5–10) supergiant fields (Ghawar, Abqaiq, Berri, etc.), with comparatively minuscule production capacity in smaller fields (Simmons 2005, p. 89). Moreover, he points out that Saudi Arabia has reported practically no new discoveries of oil outside these supergiant field basins, despite extensive exploration over nearly all the rest of the country (although optimists dispute this) (Simmons 2005, p. 118). It is therefore a practical certainty that Saudi Arabia will not discover any more supergiant fields to augment its production capacity. In addition, Simmons points to the probable exaggeration of Saudi Arabian reported reserves figures and concludes that there is no compelling reason to believe that backup capacity exists in Saudi Arabia that could replace the possible decline of its supergiants.

Simmons then turns his focus to these supergiant fields themselves and claims that recent technical problems reported by Saudi Arabia in technical journals (e.g.,

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[7] The figure of 20 Mbpd can be attributed to IEA estimates of production in 2030, which require around 64 Mbpd from OPEC (51.8 Mbpd from OPEC Middle East) to meet the projected oil demand growth to 120 Mbpd (based on average annual growth of 1.6% YoY) (IEA 2004, pp. 81–127). If Saudi Arabia were to maintain its current market share of OPEC (1/3), then over 20 Mbpd would be required.

Society of Petroleum Engineers) suggest that these fields are unlikely to continue increasing their production output. Furthermore, he argues that to maintain the extremely high production levels that Saudi Arabia has achieved in the past, these fields have been "overproduced," the consequences of which being a compromised overall URR and a likely steep drop-off in production rather than a gradual one, once the fields' peaks are reached (Simmons 2005, p. 337). This is illustrated in Figure IV-12.

Simmons points to a variety of technical problems and practices when speaking of overproduction. One example is the early employment of water injection by Saudi Aramco in its supergiant oil fields. Water injection normally is employed as "secondary" recovery, but Saudi Aramco employed it much earlier in field life to support high flow rates. Simmons suggests that this may lead to earlier "watering out" of the fields (Simmons 2005, pp.39, 138–146, 161, 172, 319). Another technical concern is that Saudi field pressures are not stable enough to rely on high flow rates indefinitely. Simmons suggests that the current high flow rates bring Saudi fields closer to the bubble point more quickly, which he says drastically reduces production (Simmons 2005, p.135). The ultimate conclusion of these arguments is that because of the supergiant's critical importance to Saudi Arabian oil production and in turn Saudi Arabia's integral role in world production, the onset of production declines in these fields may auger the beginning of a global peak in production.

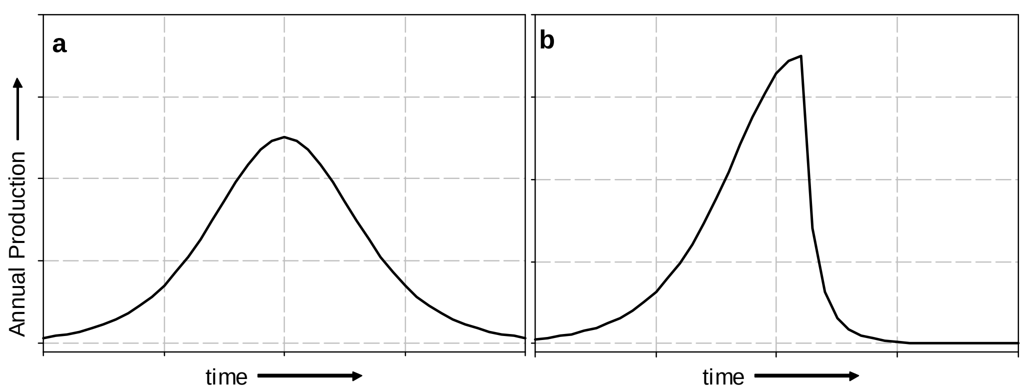

Figure IV-12. Illustration of the potential effect of overproduction as discussed by Simmons (Simmons 2005, pp.1–422). Reservoirs that are not overproduced (a) may experience a soft peak and gradual decline, whereas (b) overproduction of a reservoir to maintain production growth can lead to more sudden, steep declines when production finally peaks. The area under curve a is 20% greater than the area under curve b.

E. OPTIMISTS CONSIDER SAUDI PRODUCTION CAPACITY ROBUST

Critics of Simmons's conclusions, in particular Lynch, present at least four main counterarguments, beginning with the claim that Saudi Arabian oil production is in fact not absolutely critical to world oil supply. Every year oil industry around the world has to add at least 5–6 Mbpd of gross production capacity just to break even with the 5–6 Mbpd gross capacity is lost. Any additions to world capacity are on top of the 5–6 Mbpd capacity turnover each year. These figures are much larger than the drops in production capacity contemplated by Simmons, which would be on the order of 500 kbpd YoY. Thus, Lynch concludes that non-Saudi Arabian oil production is capable of making up losses in Saudi Arabia (Lynch 2006, pp. 1–32). Furthermore, Lynch argues that expectations of Saudi Arabia needing to increase production capacity to 20 Mbpd to satisfy global demand are greatly overstated. If Lynch is correct (Saudi Arabia need not increase production to 20 Mbpd), it implies either that the remainder of OPEC will fill in the rest or that the IEA projections of OPEC Middle East production growth (1.97% YoY) will turn out to be too high (IEA 2004, pp. 81–127).

The second important objection to Simmons' claims is that although reported reserves figures from Saudi Arabia may be open to scrutiny, the volumes of probable *resources* are much greater. He contends that resources, not reserves, are the important figure here because the Saudis have actually *not* expended much effort on exploration, and hence the amount that has been found (*reserves*) is not representative of how much oil—and hence how much potential backup production capacity—Saudi Arabia actually has (*resources*). The USGS for instance estimates a probable resource of 370 Gbbl for Saudi Arabia, which Lynch considers conservative (Lynch 2006, pp. 1–32). Furthermore, it has been argued that the well known distribution of field sizes within a given resource (which was discussed earlier) suggests that a huge quantity of oil must remain in Saudi Arabia beyond the supergiants, since a large fraction of any given resource is found within the smaller fields. Lynch reports that Ghawar accounts for about 37.8% of the URR in the Saudi Arabian basin (Lynch 2006, pp. 1–32),[8] which leaves a quantity of oil nearly two times the volume of Ghawar in the remaining fields. If Lynch's figure is accurate, however, the remaining oil in smaller fields may not be that great. When the *relative* sizes of some other supergiants are factored in, as shown in Table IV-1, the remaining fraction of URR to be held in smaller fields is around 30% of Saudi Arabia's URR.

8 USGS is referenced as the source of this figure, but it is not transparent exactly how it is arrived at (Lynch 2006, pp. 1–32).

If Ghawar and the other Saudi supergiants really represent a larger fraction of the oil endowment (URR) than the giants of most other basins, then the backup resource implied by Lynch and optimists may be overstated. Still, even in this imperfect, pessimistic estimate, the remaining resource is would be quite substantial (tens of thousands of Mbbl).

Table IV-1. Reserves estimate. Source: Carmalt and St. John 1984, pp. 11–40; Ghawar fraction of URR Source: Lynch 2006, pp. 1–32. Fraction of URR for other fields calculated based on reserves estimates.

Field	Reserves estimate in Carmalt and St. John (Mbbl)	Fraction of URR
Ghawar	82,000	37.8%
Abqaiq	12,800	5.9%
Safaniya	36,100	16.6%
Berri	12,000	5.5%
Zuluf	10,600	4.9%

A third main set of criticisms focus on Simmons's technical arguments regarding Saudi supergiant fields. Contrary to his assertions, critics claim that (1) the water cuts[9] in Saudi fields are not worryingly high; (2) the danger of a reservoir reaching the so-called bubble point is overstated—production was ramped up at Ghawar in the 1970s after it had exceeded the bubble point; and (3) there are no examples to prove that new technology currently employed in Saudi oil fields will lead to the steep drops in production as Simmons has asserted they will. On the question of water cuts, Lynch compares Ghawar, whose water cut is around 37%, to the world average, which is 75%, though it is not specified how the 75% average is calculated (volumetric average or average overall wells) (Lynch 2006, pp. 1–32). Regarding the second point, we think it somewhat audacious for non-reservoir engineers (a population that includes both Lynch and Simmons as well as the authors of this paper) to speculate on the importance of bubble-points to production levels, although the physical concept behind the problem of bubble points is simple enough to understand as described in an introductory text on the reservoir engineering.[10] Absent the experience to judge these points at an engineering

9 The water cut of a producing well is the volumetric fraction of produced materials that is water. The remaining fractions are mostly oil and gas.

10 When the pressure inside a reservoir drops to the point that dissolved natural gas begins to escape from solution inside the liquid oil, the gas begins to make up a disproportionately high fraction of the

level, Lynch's claim that Simmons provides no data from the field that actually employed the methods under question seems important.

In addition to the foregoing three main points, optimists provide a series of facts that they claim show Saudi oil production to be under no stress at all. Hence they conclude that there is no reason to expect a peak in Saudi production. Chief among these is the famously low cost of oil production for Saudi Aramco. Production cost estimates ranging from $1/bbl to $5/bbl are cited by Lynch 2006, pp. 1–32, which are much lower than those almost anywhere else in the world. Optimists contend that production costs are the surest indicator of resource maturity, and since these have not increased substantially, there is no reason to question future Saudi production capacity. Beyond this, optimists also cite at least three periods over the past 25 years (1979–1980, 1990, and 2004) when Saudi Arabia has ramped up production further and faster than any other producer in the world, as well as future capacity expansion plans, to argue that Saudi Arabia will remain the largest oil producer for the foreseeable future (Lynch 2006, pp. 1–32).

F. OUR VIEW: SAUDI PEAK NOT IMMINENT BUT CONCERNS REMAIN

In light of optimist critiques, we think that the Simmons conclusion—that a Saudi oil production peak is imminent—deserves attention but not wholesale acceptance. What most deserves attention is our remaining uncertainty about backup resources that Saudi Arabia has behind its supergiants. We agree with optimists' arguments that it is the *resources* that matter in an area that has seen little drilling, but the data presented by Lynch himself suggest that the distribution of URR may be weighted heavily toward larger fields, leaving a relatively small fraction in the remaining small fields (Lynch 2006, pp. 1–32). Still, we recognize that this would deviate from experience in other resource basins like those presented in Figure IV-5, where giant fields make up a smaller fraction. In the absence of actual exploration, though, we are left to faith in the statements of Saudi Aramco and can only speculate on how much oil remains after the supergiants in Saudi Arabia. Optimists' criticisms of Simmons's case that new production technologies may lead to steep post-peak declines and lower overall recover factors, coupled with the evidence that Saudi production costs remain low, persuade us that concern over the

material that is pumped out (produced), since natural gas is much more mobile than the oil. Consequently, a positive feedback loop is started with a too high a fraction of gas production, limiting oil production and also further reducing reservoir pressure, which in turn releases more gas from solution and increases the gas fraction produced further (Dake 1978, pp. 1–443).

supergiant fields' production reaching a peak is probably overstated. Nevertheless, we think that Simmons's general point—that production at unsafe, high levels may mask an oncoming steep decline—is worthy of notice in considering production over the longer term. Overall, the complete narrative offered by Simmons is left with some holes when critically assessed, yet his points about the importance of Saudi Arabian production, and the uncertainty about backup supply, warrant attention in the coming years.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The peak oil debate is concerned with the question of when global oil production will reach its historical maximum and enter a long inexorable decline. This paper focuses on three topics. First, we review the Hubbert theory, examine its assumptions, and note the criticism levied by optimists. We present the results of our own modifications to Hubbert's theory, which attempt to account for some of the critiques of optimists. In particular, we account for the impact of economic conditions on oil production in a simple, endogenous manner. Second, we review peakist arguments that are based on declining discovery rates. Finally, we include a section that reviews peakist concerns about Saudi Arabia's oil production in particular as described in a book by Matthew Simmons. We conclude from these reviews that the most alarmist of the peak-oil claims are likely false. Still, we see some convincing reasons to think that global production could peak within 20 years, with demand outstripping production indefinitely.

15. SUBJECT TERMS

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