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Are We Running Out of Oil ?

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Executive Summary

Since the dawn of the petroleum industry in the mid 19th century, there have been recurrent waves of concern that the exhaustion of the world's petroleum base was imminent. As early as 1874, the chief geologist for the State of Pennsylvania predicted that kerosene used for lighting would exhaust U.S. petroleum resources by 1878. But nature has consistently been far more generous than anticipated. By 1993, the U.S. had produced over 164 billion barrels of crude oil, and another 80 to 100 billion barrels are now estimated to be eventually recovered from the domestic resource base. Worldwide evidence of growing abundance is even more striking. By 1950, the world was producing 10 million barrels of crude oil a day, and proven reserves were 90 billion barrels, sufficient to satisfy then current rates of consumption for another 24 years. But in the next 43 years, 650 billion barrels were produced, as world production expanded sixfold. But still, exploration, development, learning and technology were adding reserves far faster than growing production was depleting them. Between 1950 and 1993, world reserves expanded more than tenfold to about a trillion barrels, enough to sustain 1993 production for another 45 years. Obviously, like Samuel Clemens' observation that "reports of my death have been highly exaggerated," the persistent concerns of petroleum resource exhaustion have (so far) been premature.

Virtually all empirical indicators continue to signal a growing world abundance of crude oil. Proven oil reserves worldwide are at an all-time high, and real crude oil prices are approaching record lows. Nonetheless, most recent long term oil market forecasts expect an increase in real crude oil prices over the next two decades, attributable to an expectation of increased resource scarcity. It is this stark contrast between the historical record of growing resource abundance and these renewed assertions of impending resource scarcity that motivates this study. The objective is to examine carefully both the historical record and the most prominent recent geological assessments to answer or at least address several unresolved issues. Is the long predicted "wolf" of oil scarcity finally at the door, or at least headed unambiguously toward the house? Or, on the other hand, are current perceptions of impending scarcity as myopic as in the past? Do we have sufficient information to distinguish meaningfully between the two possibilities? Does it even matter to any broader assessment of the long run sustainability of U.S. or worldwide economic growth? And finally, do either the resource prospects themselves or their implications for future supply patterns raise concerns that might call for government policy actions?

One possible explanation of the gap between experience and expectation could be faulty empirical data. An overview of the historical record of resource assessment, both in the U.S. and abroad, reveals little basis for confidence in the precision of such estimates. Not only have such estimates in the past been poor predictors of either supply or the ultimately recoverable resource base, even the most narrow and well defined of the measures (that of proven reserves) has been plagued by gross and persistent misunderstanding that has more often misguided energy policy than enlightened it. From the mid-20's to the present day, proven reserve estimates have consistently been widely interpreted as the stock of remaining resources, rather than the working inventory of the industry that it actually represents. Moreover, standards for such measurement vary widely across countries, making cross country comparisons often meaningless or highly misleading.

But the conceptual problems associated with proved reserves are generally amplified by moving to a more comprehensive measure of remaining resources, inclusive of those volumes in the earth's crust which have not yet been identified with sufficient certainty to be considered "proved." These resources consist of conventional oil yet to be discovered, further additions to reserves yet to be developed at known locations, and future increases in recovery from known sources attributable to improved economics, learning, or technical change. Almost all of these categories are unobservable, and obviously highly speculative.

Nonetheless, particularly since World War II, this information was regarded as essential. In both world wars, it was recognized that oil had become a key strategic commodity, and that most of that commodity had been supplied by domestic U.S. resources. Moreover, especially after World War II, it was becoming increasingly clear that massive low cost reserves in the Middle East would eventually draw the world into a dependence that would raise concerns about security of supply.

A large number of resource estimates, both for the U.S. and the world, began to appear after World War II. Initially, estimates for the U.S. seemed to suggest that the domestic resource base could grow almost indefinitely, as production surged to satisfy rapid growth in demand in the postwar years. By the mid 60's, estimates of the amount of oil that would be ultimately recoverable in the U.S. were approaching 600 billion barrels. But this unbridled optimism was disturbed in the mid 50's by the dissident voice of a respected geologist, M. King Hubbert, who insisted that such estimates were not only grossly overstated, but that in fact a peak in domestic supply in only a few years was imminent. This heresy initially brought Hubbert widespread professional ridicule, at least until the early 70's, when declining domestic production revealed that a peak had been crossed, timed almost precisely as Hubbert had predicted.

While the value of Hubbert's prediction continues to generate controversy, after 1970 most U.S. estimates were revised sharply downward toward levels similar to those estimated by Hubbert. However, particularly since the late 70's, official estimates have increasingly been presented as a range rather than point estimates, in an attempt to explicitly incorporate uncertainty into those estimates. As domestic production stabilized in the first half of the 80's, then resumed its fall thereafter, it has become increasingly clear that the supply potential of the domestic resource base is much more complex than the Hubbert approach would suggest. More recent resource estimates have attempted to measure the sensitivity of such estimates to factors such as technology, policy, and economics. By the 90's, estimates of the domestic resource base were again creeping upward into the 300-plus billion barrel range, nearly double the Hubbert estimates, but only about half the most optimistic estimates of the mid 60's.

World oil resource estimates have also been prepared frequently since World War II. Proven reserve estimates have been published annually for decades in several trade journals, based principally on official reserve estimates made by the major producing countries. Such estimates are even more problematic than those for the U.S., insofar as the definitions of even narrow concepts such as proven reserves differ greatly across countries. Moreover, when broader measures of resources are required (inclusive of undiscovered resources and future reserve additions at known fields), the problem of cross-country comparison is further amplified. Also, the coverage of the estimates (whether offshore resources are covered, for instance, and to what water depth) have varied over time and across estimators. Nonetheless, since the mid 60's, estimates of the world's ultimately recoverable conventional oil resources have varied over a wide range between 1.5 and 2.5 trillion barrels, but with no clear trend either up or down.

While the various assessments have their individual strengths and weaknesses, four of them are of particular interest, namely the last four assessments of conventional crude oil prepared for the World Petroleum Congress by the U.S. Geological Survey. These assessments, performed at four year intervals covering a 12 year period, use standardized resource concepts across countries, use consistent methodology over time, and explicitly quantify the uncertainty associated with their estimates. Such assessments at least address the major problems of cross-country and intertemporal comparisons which plague most of the other available world oil resource assessments, and do so over a substantial period covering the very recent past. Consequently, those four assessments provide a valuable window on geological thinking from which to examine trends with clear implications for future supply.

More importantly, perhaps, the explicit representation of uncertainty in these assessments also conveys a sense of the confidence that the assessors themselves acknowledge to be contained in their own estimates.

Several key observations arise from an examination of these assessments.

First, the most recent USGS resource assessment estimates that the total worldwide recoverable resource base of conventional oil amounts to 2.4 trillion barrels. Of that, about 700 billion has already been produced, 1.1 trillion are already identified (though mostly not yet proven, in the U.S. sense of the term), and nearly 600 billion remain to be discovered. While the "identified" category differs markedly from the proven reserves reported in the trade press for many countries, those differences are largely offsetting, so that the aggregate world total is only about 10% above the trade press estimate of proven reserves. As a consequence, the USGS 1994 assessment estimates that identified world conventional oil resources would sustain recent production rates for about 50 years, and that new discoveries would be expected to extend that horizon by an additional 25 years. Consequently, the message of resource abundance conveyed by the trade press numbers is generally upheld, and to some extent enhanced, by the 1994 assessment.

Second, there is an enormous amount of uncertainty in these numbers that is explicitly acknowledged by the USGS. In particular, it estimated that undiscovered resources could be as low as 292 billion barrels or as high as a trillion barrels, implying that the remaining world resources (sum of identified and undiscovered resources) ranges from as low as 1.4 trillion barrels (62 years) to as high as 2.1 trillion barrels (94 years) at recent production rates. As a point of reference, it is worth noting that this 700 billion barrel range between the lowest and highest of these cases is about equal to the total cumulative world oil production from 1859 until 1993.

Third, despite this wide range of uncertainty, translation of these resource estimates into plausible forecasts of world supply yield two characteristic market features that appear generally robust to variations in remaining resource volumes over this wide range. The first such characteristic is the imminence of world production decline well within the first half of the next century, for even modest levels of sustained demand growth between 1% and 2% per year. The second feature is a sharp rise of OPEC's market share, possibly to record levels, during that period of growth. These are precisely the features of the future market captured by most major forecasts. The USGS assessments appear to be broadly consistent with, if not explicitly or implicitly at the root of, such market forecasts.

Fourth, despite the wide range of the band of uncertainty considered by USGS in its 1994 assessment, there is no claim that such a range captures all of the uncertainties relevant to such future resource volumes, or even the most significant ones. In fact, USGS explicitly acknowledges that its resource estimates are static in the sense of assuming a fixed technology and current economics. Over a short time, such an assumption is of little consequence, but over a span of decades there is evidence, principally from historical U.S. data, that such changes are of major consequence, particularly as the resource base matures. Even within the span of the four resource assessments completed by USGS, covering only a dozen years, there is strong evidence that a major source of reserve additions has been missed. This evidence appears in the form of estimates plagued by a persistent propensity for being surprised. In the 1994 USGS assessment, for instance, the mean estimate of ultimate recovery was 2.4 billion barrels. A mere dozen years earlier, despite far more favorable economics expected at that time, USGS had attached less than a 10% probability to the possibility that ultimate recovery could reach such a level.

A missing source of reserve additions not captured in the USGS estimates is the revisions which occur over time as a result of slow but sustained increases in the average recovery efficiency -- the share of the original oil in place that actually is recovered before the property is abandoned. This increase results from the learning which occurs with experience in developing the known resources, and with technical change which permits more thorough resource recovery, and in some cases is due to improved economics. As a petroleum producing area matures, such improvements become an increasingly significant part of total reserve additions. In the U.S. in 1966, about 29.5% of the original oil in place discovered up to that time was thought to be recoverable. By 1979, the average recovery efficiency at that same set of fields (those discovered before 1966) had risen to 32.1%, an increase of about 0.2% per year. These small changes accounted for over 56% of the Lower 48 reserve additions during that period, exceeding the reserve additions attributable to discoveries in subsequent years.

Unfortunately, the data required to monitor these increases is no longer available for the U.S. since 1979, and has generally never been available for the world. Nonetheless, assigning plausible parameters to the world resource base suggests that such improvements could be extremely significant over a long period, with each 1% increase in worldwide recovery efficiency adding 60 to 80 billion barrels to recoverable world oil resources. Sustained increases such as those experienced in the U.S., of about 0.2% annually, would raise recovery efficiency from its current level of about 34% to as much as 54% a century hence, adding 1.2 trillion to 1.6 trillion barrels to the recoverable resource base, potentially doubling the current mean estimates of remaining conventional resources. While highly speculative, such changes can hardly be dismissed as fanciful, insofar as technologies currently available often offer recovery efficiencies well in excess of 54% in areas of limited applicability.

What then are the lessons derived from this exercise? There are two concerns that the analysis addresses, one obvious, the other more subtle.

The obvious concern, that of the imminent exhaustion of world oil, is actually the most easily dismissed. Nature continues to be quite generous in the resources available for future oil development. Identified resources alone could sustain recent production rates for about half a century, and new discoveries could easily extend this by another two decades or more. Moreover, plausible improvements in technology or simply the diffusion of existing technology could extend this outlook to a century or more. Modest growth in world demand, at 1% to 2% annual rates, could advance these peaks to the first half of the 21st century, but only the combination of an unprecedented halt in technological improvement and extremely disappointing volumes of new discoveries could lead to a resource constrained peak in world production as early as two decades hence. Even if world supplies peak within the first half of the next century, the subsequent decline is likely to be extremely slow, insuring that conventional oil could remain a major source of world energy supply well into the latter half of the 21st century. Moreover, even if the most pessimistic of the conventional oil resource scenarios should materialize, normal market processes would trigger higher prices to improve recovery efficiencies from conventional sources and potentially bring into production unconventional oil resources known to exist in extremely large magnitudes in the Western Hemisphere.

However, there is a second concern that cannot be so easily dismissed. The optimism expressed above pertains strictly to the *potential* supply made available by nature. But the resource opportunity afforded by nature is a *necessary* condition for future supply growth, not a *sufficient* one. Even identified conventional oil resources require a substantial development effort to translate such resources into actual supply. Even a modest 1% to 2% annual growth will require between 7 and 15 million barrels of new supply within a decade.

While development of incremental supply capacity at such a rate is by no means unprecedented, this development continues to occur against a backdrop of highly politicized institutional constraints in most of the major oil producing areas. While the failure of socialism worldwide has revived a commitment to markets and privatization of the oil industry in a large and growing number of countries, major institutional barriers to new supply remain in virtually all of the major producing areas. In the United States, regulatory constraints seriously restrict access to the most promising domestic petroleum prospects. In the Former Soviet Union, major issues of taxation, property rights, revenue sharing, and contract enforcement need to be settled in Russia, and several of the bordering states face serious political obstacles to the establishment of transportation links over hostile or politically risky routes. In Mexico, the liberalization and privatization in many sectors of the economy has to date not been extended to most portions of the petroleum sector. In the Middle East, there has been only very limited attempts to privatize the petroleum sectors or open access to foreign capital, and in some of the recent attempts to do so, sanctions by the U.S. have attempted to deliberately thwart the effort. Most of the countries of the Gulf continue to flirt with potential future supply restrictions via OPEC to address short term fiscal difficulties, as if past attempts to do so had not discredited such efforts, and seemingly oblivious to the potential damage that such flirtations have in compromising the perceived reliability of oil as an energy source. At the same time, terrorism, weapons proliferation, and internal and external disputes among the Gulf states offer the constant threat of future supply disruptions in a key producing region. Thus, there are an array of institutional hazards to the supply growth that will be required to satisfy growing world demand.

Finally, we come to the question of why these resource assessment exercises are even necessary. Generally, such efforts have been motivated by government concern that markets were incapable of preventing exhaustion of finite resources, or even signaling its imminence, and that government action was required to facilitate the transition to alternate fuels. Such assessments, in principle, were designed to signal the imminence of such exhaustion. In fact, while there is historical experience with fuel transitions, the historical record provides no illustrations of government ability to effectively aid in such transitions. In fact, that record is rife with examples of repeated attempts by government to allocate energy resources in response to real or perceived crises, usually in ways that aggravated the perceived problem by defeating the price signals via which energy markets themselves can be expected to generate and utilize the information required to reasonably guide such transitions.

Whether necessary or not, there are both promising and troubling features of future world oil markets that these assessments point out. Most obviously, they point to the continued abundance of energy resources that nature continues to provide. More importantly, they point out the need for major new world supply additions to sustain even modest rates of growth in world demand. Whether or not the opportunities afforded by nature are in fact realized will hinge more on success in overcoming an array of institutional barriers than it does on resource constraints.

There is a role for government here, but it is not one of micromanaging a transition to alternate fuels in time to avoid an imminent shock of global resource exhaustion. Rather, the appropriate role is a very traditional one. Internationally, it involves pursuing traditional diplomatic and military means to protect growing world trade, in energy as in other goods, and to encourage the free flow of capital to enhance prospects for world supply growth and diversification. Domestically, government has responsibilities to provide a reasonable regulatory framework for continued domestic supply development in a manner consistent with environmental protection. In the case of domestic resources on public lands, government has stewardship responsibilities to protect those lands from environmental degradation, without compromising its fiscal responsibilities to this and future generations of protecting the economic values associated with the mineral wealth of those properties.

There is a very real danger that attempts by government to address the non-problem of resource exhaustion will distract from or even aggravate the real challenge of removing remaining institutional barriers to supply growth.

Chapter 1.
Introduction

"...Hurry, before this wonderful product is depleted from Nature's laboratory!"
-- advertisement for "Kier's Rock Oil", 1855
(four years *before* the first U.S. oil well was drilled)

"...the peak of [U.S.] production will soon be passed -- possibly within three years.
-- David White, Chief Geologist, USGS, 1919

"...it is unsafe to rest in the assurance that plenty of petroleum will be found in the future merely because it has been in the past."
-- L. Snider and B. Brooks, *AAPG Bulletin*, 1936

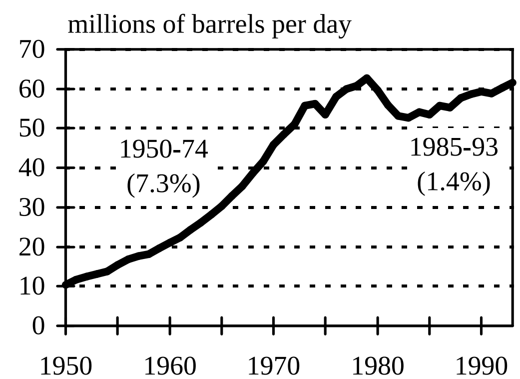
"Past...prophecies of "reserves running out" have been notoriously erroneous, but finite resources have by definition a finite existence. Perceptions of impending shortfall will cast a shadow forward, well into the period between now and 2020."
--World Energy Council, *Energy for Tomorrow's World,* 1993

Motivation

Since the dawn[1] of the petroleum industry in the mid 19th century, there have been recurrent waves of concern that exhaustion of the world's petroleum resource base was imminent. In the light of historical hindsight, such concerns of exhaustion have been obviously premature. Despite the inevitability of an eventual peak and decline in world oil production at some future date, there is little empirical evidence to suggest that such a date will be any time soon, or that it will result from global resource exhaustion.

In fact, the available empirical evidence suggests just the opposite -- by most measures, world oil resources are more abundant today than ever before. World production in recent years has resumed the growth that was briefly interrupted in the 70's and early 80's (though at a lower rate), as seen in Figure 1.

Figure 1. World Crude Oil Production[2]



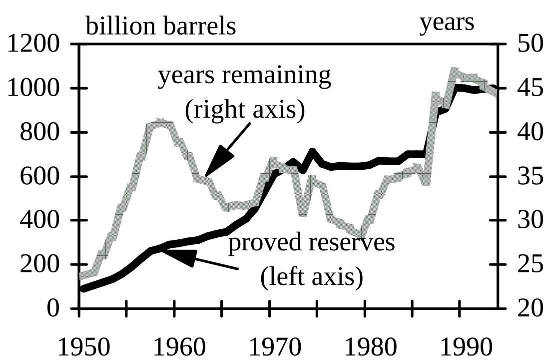
[1] While the "dawn" of the petroleum industry in the U.S. is usually considered the drilling of Drake's well in Titusville, Pennsylvania in 1859, actually petroleum is one of the oldest substances used by mankind. Greek legends indicate an understanding of the properties of "burning water," used as a weapon in sea battles. Noah is said to have caulked his ark with pitch gathered from the shores of the Dead Sea. Nehemiah used "napthar" for altar fires. Ancient Syrians mixed petroleum with ashes for use as fuel. Zoroastrians worshipped in the glow of burning gas at Baku on the Caspian Sea. Native Americans, and later European settlers in the area of New York, Pennsylvania, and Ohio, used crude oil for medicinal purposes. George Washington acquired a parcel of land in western Pennsylvania known to contain a natural seep which he called a "burning spring." All these early uses were supplied principally by naturally occuring seeps. Later, in the 19th century, oil was occasionally found by accident in drilling shallow brine wells in search of salt, and such oil was principally used for lighting. The technology of drilling such shallow brine wells inspired Drake to drill his first oil well.

[2] Unless otherwise stated, supply for this study is taken to mean crude oil only.

World production rose more than sixfold between 1950 and its peak in 1979 (at nearly 63 million barrels a day). After a sharp decline in the first half of the 80's attributable to the Iran/Iraq war and an ultimately futile attempt by OPEC to defend an unrealistic price, supply began growing again after 1985, averaging about 1.4% per year since that time, and is expected to soon surpass the previous peak.

Despite this massive expansion of supply, there is little evidence of the effects of depletion available in the historical record. As seen in Figure 2, in 1950 proven reserves were 90 billion barrels, sufficient to sustain production at the 1950 rate for about 24 years. By 1993, reserves had expanded to nearly a trillion barrels, sufficient to support 1993 levels of production for another 45 years. Moreover, this more than tenfold expansion of proven reserves occurred despite the fact that 650 billion barrels had been consumed in the interim.

Figure 2. World Crude Oil Reserves



However, there may be less here than meets the eye.

"Proven reserves" do not, have not, and were never intended to provide a measure of remaining resources, or even an approximation to such a measure. Rather, they are and always have been defined to represent a working inventory, continually replaced by new exploration and development. Current reserve estimates no more represent the remaining supply of oil resources than current inventories of groceries on the shelf are a measure of future food supplies[3]. Nonetheless, the level of proven reserves at any point does say *something* about future supply potential. Namely, it generally provides a *lower* bound on remaining resource potential[4], rather than the *upper* bound it is often misinterpreted to represent.

That upper bound, the amount of oil remaining in the earth, is clearly finite and, unlike proven reserves, clearly declines with cumulative production. However, its magnitude is unobservable, and more importantly, it is not clearly even relevant to the imminence of exhaustion. That is, oilfields are typically abandoned far before the oil in place is completely removed. On average, only about a third of the oil is recovered at the point where it typically becomes technically or economically impractical to continue production.

Consequently, the "remaining resources" of oil to be developed in the future lies somewhere between the level of proven reserves and that of remaining oil in place, with the actual level determined as much by technology and economics as geology.

Assessing the future path of such constraints is highly speculative, but one signal of increasing resource scarcity would be that of sustained long run increases in the price of oil. *Ceteris paribus*, as resource development proceeds to progressively lower quality deposits, depletion will raise replacement cost. But in practice, *ceteris paribus* often doesn't hold long enough to be of much consequence. That is, as depletion drives costs up, experience and technological change drive it down. At some point, depletion

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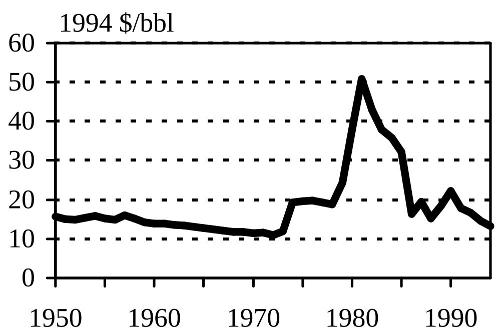
[3] Proven reserves here are taken from *Oil and Gas Jounal*, "Worldwide Issue," various years. While these are the most widely cited reserve estimates, they are generally close or equal to the official estimates for each country. As discussed later, this is a potential problem, since there is a very wide assortment of definitions and motives for such official estimates across countries. In particular, standardized financial reporting requirements give rise to United States reserve estimates far more narrow than those of most other countries.

[4] While definitions vary, the quantities represented by proven reserves are producible with existing technology and economics. While there is still some nonzero probability that such volumes could be overstated, the proven reserve classification is intended to indicate an extremely high probability of that future production. will be both technically and economically feasible.

may get the upper hand, signaled by a sustained increase in market price.

However, an examination of world oil prices provides no evidence that the market is signaling such an alarm. As seen in Figure 3, the sharp increase in prices in the 70's was not such an alarm. By now, those increases have already been largely reversed. In real terms, recent prices of crude oil are similar to those of 40 years earlier, despite the fact that the world consumed over 650 billion barrels of oil during that period.

Figure 3. Crude Oil Prices[5]



Nonetheless, despite growing world production of crude oil, proven world reserves at an all time high, and crude prices (in real terms) at levels no higher than in the fifties, most recent long run forecasts of world oil market trends estimate that real oil prices will rise over the next decade[6], owing largely to expected declines in world oil supplies by early in the next century.

These current "warnings" claim to be more credible than those of the past (although not surprisingly, past assessments claimed greater credibility than their own predecessors[7]). Such improvement is claimed on the basis of superior technology and/or the accumulation of knowledge from progressively more extensive exploration and development efforts. And of course, accumulated knowledge should improve the accuracy of any set of estimates over time.

Beyond this, the credibility of recent worldwide resource assessments has been bolstered by three facts.

First, the world has already experienced serious oil supply scarcity, in adapting to the supply restraints imposed by OPEC from 1973 to 1985. While hindsight makes it clear that this was a scarcity contrived by the OPEC cartel, rather than the result of a resource constraint, the distinction often is not made[8].

Second, in two of the largest three oil producing areas, the United States and the Former Soviet Union, production has peaked and is declining. While in both areas there are clearly factors other than resource constraints at work[9], the relative importance of such entangled factors is often hard to identify[10].

Finally, and perhaps most importantly, past concerns of imminent exhaustion were usually quickly discredited by the discovery of major new supply sources which supported continued supply growth, or the imminent development

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[5] Measured as average U.S. wellhead value, expressed in 1994 dollars computed using the U.S. GDP deflator.

[6] See, for example, International Energy Agency [1994], U.S. Department of Energy [1995], World Energy Council [1993], Energy Modeling Forum [1992].

[7] For example, the 1922 USGS/AAPG study claimed that "Fortunately estimates of our oil reserves can be made with far greater completeness and accuracy than ever before."

[8] At least the long run effects were contrived. That is, the 1973 supply interruption was associated with the use of oil as an "economic weapon" in an Arab embargo against the U.S. and the Netherlands in response to their support of Israel in the 1973 Arab-Israeli War. Similarly, the 1979-80 disruption was associated with the revolution in Iran and subsequently the outbreak of war between Iran and Iraq. Neither disruption could be characterized entirely as contrived. Nonetheless, the supply behavior in response to those disruptions was clearly contrived, as potentially offsetting unused capacity in the other OPEC countries, particularly those in the Gulf, were deliberately left idle in a lengthy attempt to artificially maintain oil prices.

[9] That is, political and institutional barriers to upstream investment in the FSU, and constraints on land access in the United States, have played extremely significant roles in supply limitations in each area.

[10] The role of resource constraints and government policy are often difficult to disentangle, because misguided policy may generate self-fulfilling expectations. For example, domestic price controls and allocation schemes in the U.S. in the 70's gave rise to real shortages by crippling ordinary market responses which would have restrained demand and encouraged domestic production. In so doing, it aggravated the international problem (i.e., it artificially stimulated U.S. import demand, both by encouraging consumption and discouraging domestic supply), and reinforced public perceptions of shortages.

of discoveries already made. Now, however, there have been no new discoveries in the past several decades of sufficient magnitude to substantially alter periodic geological assessments of world crude oil resource potential.

It is the stark contrast between this recent historical record of growing resource abundance and a renewed consensus of impending resource scarcity that motivates this study. The objective is to examine carefully both the historical record and the most prominent recent geological assessments to answer or at least address several unresolved issues. Is the long predicted "wolf" of oil scarcity[11] finally at the door? Or, are current perceptions as myopic as in the past? Do we have sufficient information to distinguish meaningfully between the two possibilities? And finally, how important is it that we do? In particular, is there a case for broader government intervention in petroleum markets to correct for a failure by markets to signal impending resource scarcity?

Organization

The first task, addressed in the next chapter, is to review the long history of geological estimates of remaining resource potential, both in the U.S. and, more recently, the rest of the world.

There was a steady increase in the assessed volumes remaining to be produced by the domestic industry from the turn of the century until the early 60's, suggesting a strongly conservative bias to those estimates[12]. Experts were repeatedly subjected to large surprises in supply potential year after year. By the 60's, a strong debate developed in the geological community over the sustainability of growth in domestic supply. The range of estimates of the total volumes which would ultimately be produced in the U.S. expanded greatly, with the high estimates (nearly 600 billion barrels) triple or even quadruple the volumes of the low (150 to 200 billion barrels).

After U.S. production peaked in 1970, fulfilling the predictions of the pessimists in this running debate, most estimates of remaining potential fell sharply. More recently, those estimates of U.S. potential have begun to rise again, though such estimates are increasingly qualified to recognize their very strong sensitivity to economics and technology. Ironically, the recognition of such increased domestic resource potential has coincided with one of the sharpest declines in domestic upstream activity in history, not the result of a resource constraint, but rather to the availability of more competitive, lower cost resources abroad, combined with progressively more severe policy restraints on access to the most promising remaining domestic resources.

Next, the chapter turns to estimates of worldwide supply potential. While several official estimates of this potential were made well before the 1920's, the frequency and significance of the estimates increased rapidly after World War I, which had demonstrated that oil was a key strategic commodity in modern mechanized warfare. World War II reinforced this strategic importance. By that time it was clear that the world's largest and least costly oil resources were not in North America but in the Middle East. It became apparent that imports of petroleum would play a significant role in U.S. oil supply (not to mention a far more significant role in the postwar economies of Europe and Asia).

Again, there was frequent concern that worldwide resources were in danger of exhaustion. Geological estimates of remaining worldwide potential began to appear on a regular basis. Early estimates grew steadily, as they had in the United States, and were usually rather quickly overtaken by actual production. More recent estimates, while fluctuating by large amounts, have not exhibited any clear trend since the mid 70's, despite the rapid pace of worldwide industry growth and geographical dispersion in the postwar period.

What emerges from Chapter 2 is a somewhat chaotic history of geologists' attempts to

[11] Metaphor used by Akins [1973].

[12] That is, estimates of remaining potential were usually exceeded by actual production within a short period following the estimate.

estimate the world resource base during this period, and the implications of these resource limits for future supply. While it is clear that many past estimates of the U.S. resource base have been overly conservative, not all have been so. In fact, in light of the decline experienced in U.S. production since 1970, estimates of domestic resource potential were revised sharply downward. Similarly, estimates of worldwide resource potential, made principally since World War II, ended their upward trend in the mid-60's. Generally such estimates have been interpreted as implying that sustained modest growth in world oil supply may not be feasible beyond the first half or even quarter of the next century.

Chapter 3 examines this proposition, taking the most recent worldwide resource assessment prepared by the U.S. Geological Survey as given, and examines its likely implications for future world petroleum supply. What emerges from this analysis are two characteristic features of the current conventional wisdom, both of which follow directly from geologic constraints contained in the USGS assessment. First, it appears that, under plausible assumptions, world petroleum supply will peak early in the next century. Second, it appears that, because of the heavy concentration of remaining conventional petroleum resources in the Middle East[13], world supplies will eventually become increasingly concentrated in that region. Nonetheless, the assessment also admits to a sizable band of uncertainty that must reasonably accompany any estimate of future supply potential. Even when only that portion of the uncertainty associated with the level of future discoveries is considered, the difference between the high and low estimates of future discoveries amounts to nearly 700 billion barrels, roughly equivalent to cumulative world consumption from 1859 to the present.

But even this broad band only partially captures the uncertainty surrounding future supply potential. That is, the level of future discoveries is not the only source of uncertainty affecting future oil supply. It may not even be the most important one. Economics and technology are explicitly assumed to be static in the USGS assessments. This is a useful convention to follow, insofar as it provides a standardized "format" to facilitate comparisons among expert geologists, thereby providing a basis for aggregating their results to worldwide totals. However, it has drawbacks, as well. Most importantly, it fails to capture effects that, while difficult to predict or even quantify, are clearly neither static nor inconsequential. On the contrary, technology and economics are widely recognized to have major implications for future supply potential, as they have in the past.

Chapter 4 develops this treatment of uncertainty further, with an examination of the sensitivity of the geologic assessments to plausible variations in economics and technology. It indicates that, while a peak in world oil supply *might* well be reached in the first half of the next century, it is certainly not necessary. Other plausible scenarios, such as low growth in world demand coupled with modest but sustained technological improvements which increase average recovery rates, could postpone the peak of world production until well after 2050. Even in these cases, however, not much more than half of the conventional oil in place is actually recovered, nor are the enormous known volumes of unconventional oil resources, primarily in the Western Hemisphere, significantly touched.

With this assessment as background, Chapter 5 addresses what is perhaps the most important question posed by these data, which is -- "so what?" That is, are there features of this outlook that are cause for concern, and if so, can those concerns be remedied by government action? Specifically, there are two concerns to be addressed -- one imaginary, the other very real. More importantly, there is a role for governments here, but a danger that misguided actions aimed at the imaginary concern may neglect, distract from, or even aggravate the real one.

Chapter 6 summarizes the study and its principal conclusions, which are threefold.

[13] See Energy Modeling Forum [1992] for a comparative review of forecasts from a set of the most commonly used world oil market models. These two characteristics -- growing resource scarcity and growing supply concentration in the Middle East, are common to virtually all of the forecasts prepared by the modelers. This is perhaps the most enduring characteristic of most forecasts since the mid 70's (see Lynch [1992]).

First, resource availability is not likely to be a binding constraint on supply growth for at least several decades, quite possibly far longer. Second, however, expansion of such supply at even modest growth rates will require substantial new investments in capacity over the next decade, of a magnitude that will be formidable under even the most optimistic of world investment climates. Finally, however, realizing such potential gains may be seriously threatened by institutional barriers in all of the largest current producing countries (the U.S., the FSU, Mexico, Venezuela, and the Persian Gulf), despite the fact that such barriers have been declining in many other areas since the collapse of socialism. It is these institutional barriers that are likely to be more serious impediments to future worldwide oil supply growth than any scarcity imposed by nature.

Chapter 2.
The Record of Oil Resource Assessment

> "Essential materials in our civilization are wood, water, coal, iron, and agricultural products. ... We have timber for less than 30 years. ... We have anthracite coal for but 50 years, and bituminous coal for less than 200. Our supplies of iron ore, mineral oil, and natural gas are being rapidly depleted, and many of the great fields are already exhausted.
>
> -- Pinchot, G., *The Fight for Conservation*, 1906

An Old Question: How Much is Left?

Petroleum *is* an exhaustible resource. Like coal and natural gas, it was originally generated by infinitesimally slow geologic processes occurring over a span of millions of years, in which fluids and gases from organic matter were trapped in the pore space of sedimentary rock formations. At such a pace, the amount of natural replacement occurring over the span of even a few hundred years would be trivial, so for all practical purposes the volume of original oil-in-place in the earth's crust at the birth of the petroleum industry in the mid-19th century imposes an upper bound on what can ultimately be produced over the industry's entire lifetime.

Consequently, in a (trivial) sense, we are always "running out" of oil in the sense that each barrel consumed brings us precisely one barrel closer to that upper bound. That is, at any moment, the amount of resource remaining is simply this upper bound less the cumulative production up to that point. If this upper bound were known with certainty, and consumption was expected to grow indefinitely, the imminence of exhaustion would require a simple calculation comparing expected rates of consumption to this stock of remaining resource.

But of course, this is a very big *if*. While production volumes are measured with relative precision, the remaining resource volume is completely unobservable and consequently highly speculative[14]. Moreover, there are prices in the range of historical experience at which world consumption has stopped growing, or even declined, as was seen in Figure 1.

At some point, of course, oil use *will* be displaced by some other fuel, just as U.S. coal consumption in some uses was replaced by oil in the early part of this century, or wood was replaced by coal in England at the onset of the industrial revolution. Seldom if ever has such a transition been due to exhaustion of the resource or even to increases in resource cost. Rather, it often simply represents the emergence of a new use in which an alternative fuel has one or more characteristics superior to its predecessor[15]. As a consequence, both the amount of oil originally in the ground at the industry's birth and the amount remaining after the industry's demise are both unknown numbers, not necessarily of significant empirical importance. Nonetheless, those numbers have always been of interest, both to the industry

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[14] There are a number of reasons why oil and gas deposits pose uncertainties quite different from other mineral resources. First, there are currently no known technologies for establishing the existence of such resources short of drilling the prospect. Other minerals are often identified by outcroppings or by exploratory techniques less expensive than oil drilling. Second, even if a well confirms the existence and areal extent of an oil or gas resource, the amount recoverable depends on the mobility of the resource within the formation and the technology and production methods used.

[15] The initial use of oil was for lighting, not transportation. Some of the early warnings of exhaustion were expressed as fears that the "lights will go out." Many of these concerns were expressed well before the scope of oil's principal use -- as a transport fuel, was even appreciated.

itself and to governments with an interest in their activities[16].

This chapter examines the history of attempts to estimate how imminent the exhaustion of oil resources is likely to be. We begin with an examination of the U.S. experience, which is useful for two reasons. First, since the U.S. was, and still is, both a major world producer of crude oil, and a major developer of standards and industry practices for the estimation of petroleum resources, its future prospects are not an insignificant part of the world petroleum outlook. Second, the U.S. experience may hold valuable lessons for the future prospects of other, younger, producing provinces around the world. The experience of those other areas comprises the second part of the chapter, while the final section presents an interpretation of the significance of such experience for future world supply prospects.

Estimating Petroleum Resources: The U.S. Experience

Estimates of the amount of oil remaining in the earth's crust are extremely uncertain[17], for a number of reasons. First, the location and volume of the resource in the earth's crust at any time is only partially known, since not all prospective areas of the globe have been explored, and many of those which have been explored are not fully developed or even delineated. Second, resources are highly variable in quality and form, so that the cost of extracting the resource is similarly variable. Quite unlike the common misperception that oil occurs in large underground "pools,[18]" oil actually occurs in the pore space of sedimentary rocks[19], and the characteristics of that rock and the oil it contains determines the effort required to extract the resource. This gives rise to uncertainty not only about the volume of oil that exists, but also to uncertainty about how much of that volume will eventually be economically and technically feasible to produce.

Typically, exhausting the oil in place (recovering 100% of it) would require mining the reservoir rocks, which even if it were technically possible[20], would not likely be economically feasible. Over the history of the U.S. industry, for example, only about a third of the estimated oil in place at known fields has typically been recovered. The remaining two thirds of the resource remains as a potential target for new technology and/or future improvements in market conditions. Despite the obvious problems that these characteristics create for reliable estimation, estimating the remaining recoverable resource has been a perennial activity throughout the history of the U.S. petroleum industry.

Early Estimates of Remaining U.S. Oil Resources

The U.S. oil industry was born in 1859 with the drilling of the first well in Titusville, Pennsylvania. By the turn of the century, the United States had produced about 1 billion barrels of oil. Within 9 years, that total had doubled, and a 1909 report by the US Geological Survey[21] estimated that between 10.0 and 24.5 billion barrels would ultimately be produced, which would be exhausted by about 1935. By 1915, new USGS reports[22] estimated that this was too optimistic, and that the original resource was only 9 billion barrels. In 1916, in a report to the U.S. Senate[23], a Bureau of Mines geologist asserted that the peak in US

[16] Such interests changed many times over the past century -- from concern over monopoly behavior by the Standard Oil Trust, to supply of fuel to the military, to conservation concerns associated with the rule of capture, to concerns about import dependence and pricing/marketing practices.

[17] This uncertainty is greater for oil than for other resources, such as coal, since the petroleum resource is mobile within the source rock, and the degree to which this mobility can be exploited is a major factor in determining the rate of recovery of the resource from that source.

[18] The industry often compounds the misperception with its own terminology. "Pools" is a good example of such a poor choice of technical terms.

[19] The word "petroleum" literally means "rock oil", from the Latin "petra", meaning "rock" and "oleum", meaning oil.

[20] Although well before the drilling of Drake's Pennsylvania well, California oil had been recovered by mining techniques.

[21] See Day [1909].

[22] See Arnold [1915].

[23] Response by Secretary of Interior to Senate Resolution. Appears in U.S. Senate, Document 310, 64th Congress, First Session, Feb. 2, 1916.

oil production would occur within five years, and that "with no assured source of [new] domestic supply in sight, the United States is confronted with a national crisis of the first magnitude." Estimates of both original and remaining resources crept up through the period of World War I and the early 20's, although the estimators typically expressed great confidence in the imminence of exhaustion implied by their numbers. White [1919] expected exhaustion in the early 20's, while Gilbert and Pogue [1918] (of the Smithsonian) not only predicted imminent exhaustion but were so confident as to say that "there is no hope that new fields, unaccounted in our inventory, may be discovered of sufficient magnitude to modify seriously the estimate...[The war] has merely brought into the immediate present an issue underway and scheduled to arrive in the course of a few years."

These early estimates were plagued by a number of problems. First, resource definitions were highly subjective, ambiguous, and evolving[24]. Second, as actual cumulative production moved closer to estimates of total resources that had been made only a few years earlier, the credibility of such estimates was repeatedly undermined.

This led to a general recognition of a conservative bias to such estimates, and to attempts to qualify those estimates sufficiently to reduce this bias. Geologists increasingly recognized that their estimates covered only a portion of future supply potential, predominantly that associated with known producing areas, and sometimes areas with potential highly analogous to known areas. The USGS/AAPG report in 1922 used the term "reserves" to describe their 9 billion barrel estimate of remaining resources, although they divided this aggregate into two categories -- 5 billion barrels of "oil in sight," and 4 billion as "prospective and possible. The former category it judged as "reasonably reliable," the latter "absolutely speculative and hazardous[25]."

Emergence of Formal Reserves Concepts

This distinction became much sharper by 1925, as the American Petroleum Institute, in response to the Federal Oil Conservation Board[26], prepared an estimate of domestic "proven reserves," defined as the volumes of crude oil which geological and engineering information indicate, beyond reasonable doubt, to be recoverable in the future from an oil reservoir *under existing economic and operating conditions.* Perhaps equally if not more significant was the choice of the API to explicitly *exclude* from such measure any estimate of (a) future reserve additions at known fields that are probable but not yet proven, and (b) future reserves from

[24] The earliest estimate shown here, by Day in 1909, is often cited as evidence of the ridiculously conservative bias in geological assessments. However, in examining the statement carefully, what stands out is the imprecision of what exactly he is talking about. One interpretation, usually attributed to him, is that he was predicting total resources that would ever be recovered from the United States, which with hindsight is ludicrous. Another more charitable interpretation is that he was referring to ultimate recovery from properties known in 1909. He begins his report with the statement that "This report ... is limited to the petroleum fields actually developed, or what is known as 'proved territory' " (principally Pennsylvania, Ohio, and West Virginia, for which his estimates in retrospect appear reasonable). Nonetheless, throughout the report references to the U.S. do not appear to be similarly qualified.

[25] There was also a limited understanding of the factors leading to resource origin and occurrence, which led to many classic missed opportunities. Pratt [1952] notes, for example, that in the 15 years prior to the discovery of oil in Kuwait, three of the world's largest oil companies had been offered for a nominal consideration the right to explore for oil. All three declined, doubting suitable conditions for oil, not out of ignorance, or lack of evidence (prolific seeps of oil were long known in Kuwait), but based on their extensive experience in Iraq and Iran. The company that subsequently took the opportunity, Gulf, was far less familiar with the area, thus not convinced that "there was no oil left to be found in Arabia." DeGolyer [1960] makes "a plea for loose thinking" in an address to the AAPG, suggesting that theories of origin and occurrence are too uncertain to be regarded as anything more than tentative hypotheses, and that "as much oil may be found in the future with new viewpoints as with new techniques."

[26] The Federal Oil Conservation Board had been set up by President Coolidge in 1924 to "study the government's responsibilities [and] enlist the full cooperation of representatives of the oil industry [to] safeguard the national security through conservation of our oil." The security concern stemmed from the realization that 80% of the oil used in World War I had been supplied by the United States, combined with the fear that domestic resources were nearing depletion.

Table 1. Early Estimates of U.S. Oil Resources, 1908-21
(billions of barrels)

End of	Author	Past Production	Remaining Oil	Total Resource
1908	Day [1909]	2.2	7.8-22.1	10.0-24.5
1914	Arnold [1915]	3.3	5.8	9.1
1915	USGS [1916]	3.6	7.6	11.2
1916	USGS [1917]	3.9	6.2	10.1
1918	White [1919]	4.6	6.7	11.3
1919	White [1920]	5.0	7.0	12.0
1921	USGS / AAPG [1922]	5.9	9.2	15.1

undiscovered fields, on grounds that "an estimate of reserves which are to come from fields yet to be discovered involves so many uncertainties that it would be grossly inaccurate and misleading."

This did not imply any lack of optimism in the petroleum industry for future domestic discoveries. In fact, in these early reports, API noted that unexplored areas could be *expected* to be the major source of future supply. Unexplored areas were called the country's most precious asset, reflecting a recognition that reserves were not synonymous with remaining resources, but that the expected volumes from those unexplored lands were to uncertain to permit quantifying their potential.

The API continued to issue reports on U.S. proven reserves, in 1934, in 1936, and annually thereafter until 1979, when the oil reserve estimation function was officially taken over by the U.S. Department of Energy[27]. While the API definition of proven reserves provided a standard for resource measurement[28], it was clearly and deliberately intended to be a very narrow measure, which the API, and later the Department of Energy, emphasized covered only a small portion of the expected remaining resource base. While that narrowness was intended to facilitated clarity[29], in fact it often did (and continues to do) precisely the opposite. By adopting terminology with familiar non-technical meanings (such as reserves), and assigning them definitions far more narrow than those conventional meanings, the terms themselves often promoted (and continue to promote) fundamental misunderstanding of resource scarcity, even within the industry itself.

The most common of these misunderstandings involved the misinterpretation of reserves as a comprehensive measure of remaining resources. By 1925 the term was already closely associated remaining resource supply potential, despite clear qualifications by the industry itself that such an interpretation was wrong. The API definition of proven reserves clearly asserted that the measures provided had no bearing whatsoever on remaining supply potential.

This was also clear from examination of the data itself, as seen in Figure 4. Proven reserve estimates did not vary greatly over time[30], always running somewhat ahead of cumulative production. In 1945, for example, cumulative crude oil production in the U.S. stood at about

[27] Actually, DoE prepared estimates for 1977 and 1978 as well, for purposes of comparison with API estimates. There had been a longstanding suspicion within government that industry estimates were deliberately estimated too low (see Wildavsky and Tenenbaum [1981] for a history of these suspicions). In fact, the DoE exercise for overlapping years (1977, 1978, and 1979) was conceptually identical and quantitatively only very slightly different than those prepared by the industry for those years.

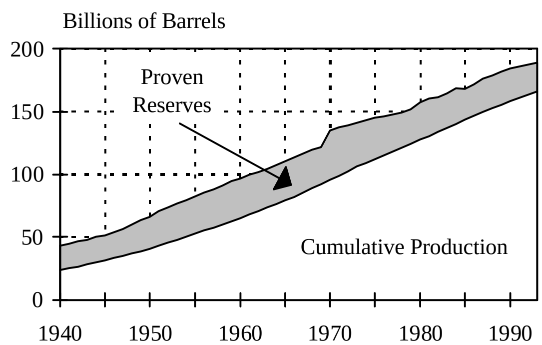
[28] Although the definition was itself prone to subjective interpretation that gave rise to continued ambiguity.

[29] The narrowness of the measure also enhanced the feasibility of accurate reporting by the companies involved, insofar as a broader measure would often have revealed longer run development strategies that individual companies would be reluctant to share with competitors.

[30] Adelman [1991] characterizes the imminence of shortages attributed to misinterpretation of reserves as "like the horizon, always receding as one moves toward it."

32 billion barrels, and proven reserves amounted to 20 billion barrels. Between 1945 and the end of 1993, however, 135 billion barrels were produced, and reserves by that time were 23 billion barrels, 3 billion barrels *higher* than reserves in 1945. Over the 48 year period, 138 billion barrels of new domestic reserves had been added, over 4 times the level of reserves at the beginning of the period.

Figure 4. U.S. Cumulative Oil Production and Proven Reserves



Obviously, proven reserves as narrowly defined by API[31] was simply a measure of working inventories of recoverable oil principally underlying existing wells within a highly restricted geographical circumference. As such, it represented a *minimum* on the remaining recoverable resource (i.e., the volume remaining to be produced if discoveries and technical change came to a halt, and economic conditions remained unchanged indefinitely), precisely the opposite of the *maximum* it is often misinterpreted to be.

Nonetheless, it was (and continues to be) often misinterpreted as an expected value for the remaining resource base. A former chairman of the API Committee on Reserves wrote in 1950 that[32] "there has been a tendency--in fact it has almost developed into a habit -- among many of those people who bemoan the diminishing ultimate supply of oil reserves, to divide the estimated reserves as of the end of a given year by the quantity of oil produced in that year, and to state that the quotient represents the number of years left...by our domestic supply.[33]"

Reserves versus Resources: Post-WWII Attempts at a Broader Measure

The rapid growth in domestic production during World War II, combined with the slowdown in domestic reserve additions attributable to unavailability of key materials (such as steel for drilling) led to new fears of exhaustion in the early postwar years, and revived concern that the war had "drained America." However, it was also clear that the narrow concept of "proven reserves" did little if anything to address this concern. Such an assessment would require a more comprehensive measure, which attempted to identify other portions of the resource base that "fueled" the growth of reserves. There were two such sources of such additions -- namely fields not yet discovered, and field growth (in both known and undiscovered areas) via improvements in recovery efficiency.

A number of resource classification schemes had emerged in the postwar era, and continue to emerge today[34]. Each of these systems differ

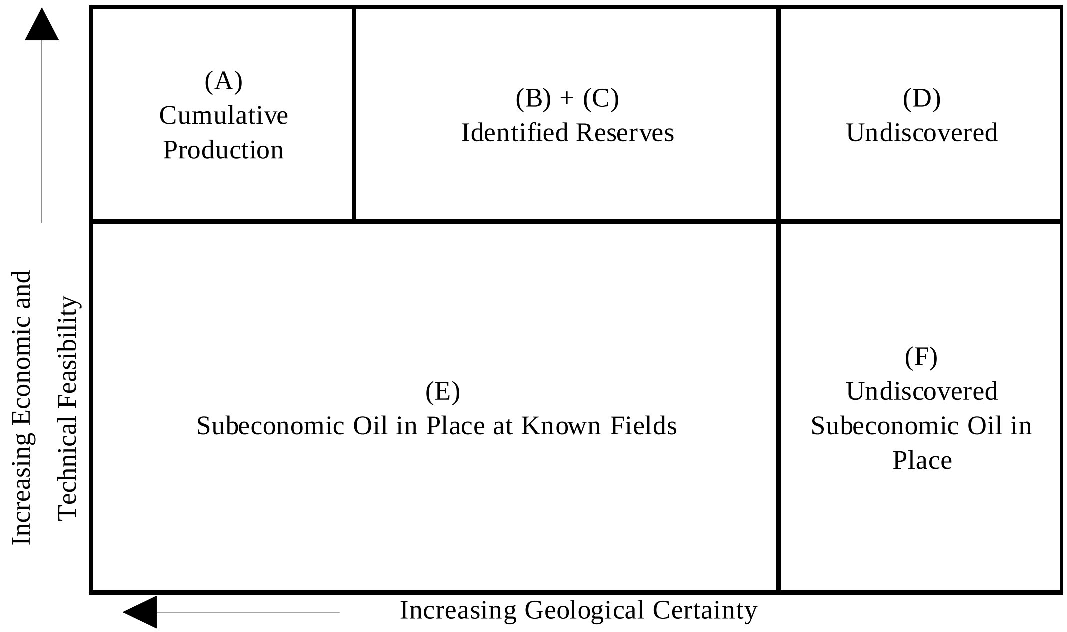
[31] The API Committee on Petroleum Reserves [1962] defined proved reserves as: "...the volumes of crude oil which geological and engineering information indicates beyond reasonable doubt, to be recovered in the future from oil reservoirs under existing economic and operating conditions..."

[32] See Lahey [1955].

[33] The term "reserve life index," calculated as proven reserves over current production rates (expressed in years) is another example of poor choice of technical language, since the term itself has a common meaning much closer to the notion of the remaining potential from depleting a fixed stock than of working inventories.

[34] There are a number of variations on these systems of resource classifications, most of which are rooted in the API definition of proved reserves, namely: "...the volume of crude oil which geological and engineering information indicates beyond reasonable doubt, to be recovered in the future from oil reservoirs under existing economic and operating conditions..." In 1987, the Society of Petroleum Engineers (SPE) advised that reserves should be "...estimated volumes of crude oil ... that are anticipated to be commercially recoverable from known accumulations from a given date forward, under existing economic conditions, by established office practices, and under current government regulations. Reserves estimates are based on interpretation of geologic and / or engineering data available at the time of the estimate. Proved reserves can be estimated with reasonable certainty to be recoverable under current economic conditions." The World Petroleum Congress (WPC) adopted a similar definition at the same time

Figure 5. Modified McKelvey Box



in significant ways, but most preserve, at least conceptually, the framework shown in Figure 5[35], which captures the dimensions of the uncertainties usually involved in such a more comprehensive measure. The horizontal axis of the box depicts growing geologic certainty as one moves from left to right. The vertical axis reflects growing economic and technical feasibility as one moves from bottom to top.

The box in the northwest corner (A) represents the cumulative sum of production to date, the only category of the resource base known with absolute certainty to have been both geologically present and feasible to have been produced. The rest of the boxes, which comprise the remaining resource as of the date of estimate, each have some degree of uncertainty. The box in the southwest corner (E) represents the remaining oil left in place after known resources are produced.

Boxes (B) and (C) contain identified resources in known locations. The volume of proven reserves, (B), constitutes only the known portion of this resource expected to be producible with current technology and market conditions. Boxes (D) and (F) are the expected volumes remaining to be discovered at some future point. The size of the entire box conceptually represents the total volume of conventional oil in the earth's crust, and the sum of boxes (B) through (F) comprise the volume of that resource remaining at the time of the estimate.

While the API chose not to engage in such speculation in its estimates beyond (B), it remained of central interest to others in both the industry and government. Moreover, both technology and information were becoming sufficiently advanced to permit geologists to make such estimates with at least a limited degree of confidence[36]. In the late 40's, a number of geologists both within industry and

(Martinez et al. [1987]). Both focus on clarifying the notion of reserves, and both attempt to develop measures of broader resource categories. Roger et al. [1994] discusses the differences between these systems, and describes the systems that specific countries now use. An additional complication arises in the case of the United States, where Securities and Exchange Commission reporting requirements impose a very narrow definition of reserves. Johnston [1995] discusses the degree to which these SEC rules interact with fiscal systems worldwide to complicate the valuation of reserves reported by U.S. companies operating internationally.

[35] This is a modified version of the "McKelvey box" developed by USGS. See McKelvey [1973].

[36] Due both to geophysical advances and to new insights into patterns of occurrence and migration of the resource (see explanations of the "Realms" hypothesis in Masters et al. [1991, 1994]).

Table 2. Estimates of the U.S. Petroleum Resource Base, 1946-1962 (billions of barrels)

End of	Author	Cumulative Production	Proven Reserves	Other Reserves[38]	Remaining Resources	Ultimate Resources[39]
1946	Pogue [1946]	33.2	20.8	50.0	70.8	104.0
1947	Weeks [1948]	35.1	21.5	53.4	74.9	110.0
1947	Pratt [1950]	35.1	21.5	85.4	107.0	142.0
1956	USDOI [1956]	55.2	30.4	214.4	234.8	300.0
1956	Pogue et al. [1956]	55.2	30.4	79.4	109.8	165.0
1956	Hubbert [1956]	55.2	30.4	64.4	94.8	150.0
1956	Pratt [1956]	55.2	30.4	59.4	89.8	145.0
1957	Hill et al. [1957]	57.8	30.3	161.9	192.2	250.0
1958	Netschert [1958]	60.3	30.5	281.2	311.7	372.0
1958	Weeks [1958]	60.3	30.5	113.2	143.7	204.0
1958	Davis [1958]	60.3	30.5	74.2	104.7	165.0
1959	Weeks [1960]	62.9	31.7	296.4	328.1	391.0
1959	Knebel [1959]	62.9	31.7	78.4	110.1	173.0
1960	Moore [1962]	65.4	31.6	269.4	301.0	364.0
1961	Zapp [1962]	68.1	31.8	490.1	521.9	590.0
1961	Averitt [1961]	68.1	31.8	300.1	331.9	400.0
1962	Hubbert [1962]	70.7	31.4	76.0	107.4	175.0

government began to present such estimates of the total resource base, which are shown in Table 2. Unlike the "reserves" estimates, these estimates *were* clearly attempts to estimate the "ceiling" on production for all time.

By the mid 50's, most of these estimates, both by industry and government, recognized that the U.S. resource base was far larger than had previously been thought, probably with an ultimate recovery in the hundreds of billion barrels[37]. However, there was a wide and growing range of disparity among the estimates, far more significant than any differences over proven reserves.

The Hubbert Dissent: Heresy or Prophecy?

These growing differences flared into an extremely lively debate in the early 60's. Official government estimates became uncharacteristically optimistic that the domestic resource base of conventional oil was massive (approaching 600 billion barrels), and would sustain continued production growth for many years[40]. But there were a number of dissenters, most notably M. King Hubbert. In a 1956 speech to the American Petroleum Institute, Hubbert suggested that these estimates were far too optimistic. Hubbert estimated that the Lower 48 states would ultimately produce between 150 and 200 billion barrels of oil, and that the peak would occur in the late 60's to early 70's. In a 1962 report to the National Academy of Sciences, Hubbert continued to argue that the ultimately recoverable resource base was only about a fourth of the most optimistic estimates, and moreover, that the peak in domestic production was quite

[37] Nonetheless, there remained a strong popular misconception, even in agencies and regulatory bodies actively monitoring industry activity, who clearly interpreted the remaining resource base as simply the volume of current reserves.

[38] Includes both probable (not proven) reserves in the vicinity of known fields as well as undiscovered reserves.

[39] Ultimate resources corresponds to the sum of (A) through (D) in Figure 5, above. Consequently, it is contingent on economics and technology available as of the date of the estimate. It is not an absolute ceiling, insofar as changing economics and technical progress could capture at least a portion of boxes (E) and (F).

[40] Despite the fact that domestic production growth was averaging well in excess of 7% per year from 1945 until 1962.

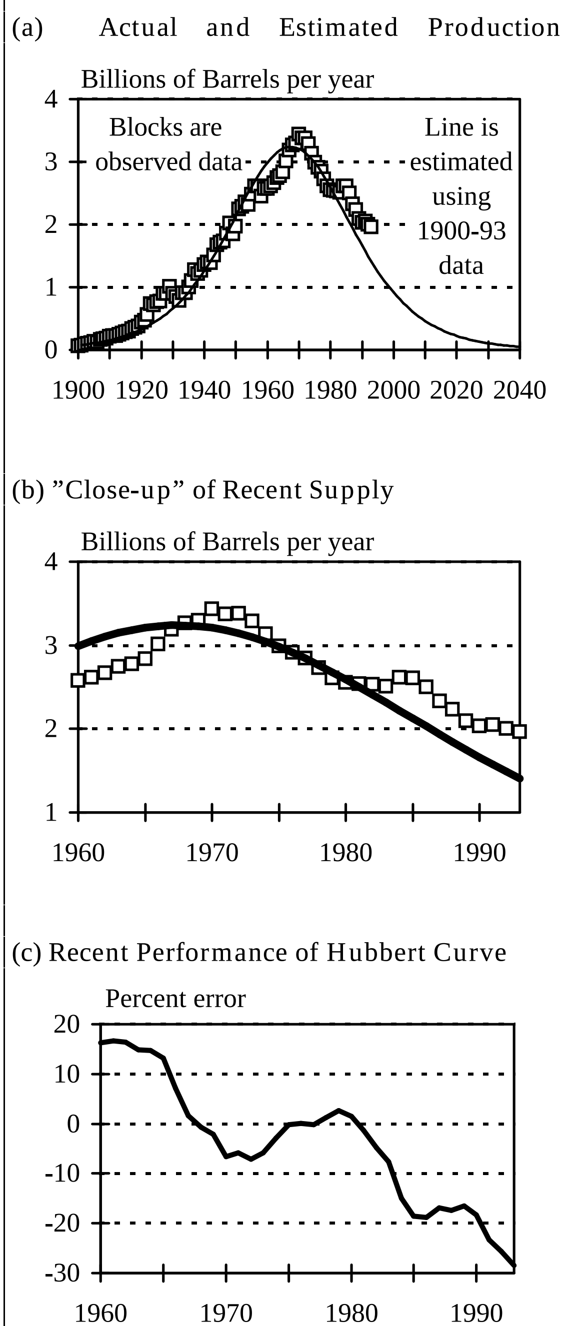
imminent. He estimated in 1962 that the peak would occur in less than a decade.

Hubbert's conclusion was based on the simple claim that any non-renewable resource would inevitably go through two phases -- a rise from zero to a peak, followed by a decline to zero, as shown in Figure 6. Of course, such a weak condition did not imply either the pattern he predicted, or even a unique global peak, let alone a relatively inflexible logistic form of the type he estimated. Such a pattern was in fact extremely restrictive. For one thing, it is symmetric. Once the peak occurs, the remaining future supply is simply twice the cumulative production at the peak, and the pattern of decline following the peak is a mirror image of the rise to the peak. Neither property has held up since 1970. Production has fallen slower after the peak than it rose prior to the peak, particularly in the 90's, and in fact actually rose in the first half of the 80's as wellhead price controls were lifted[41].

More importantly, perhaps, the ultimate recovery implied by Hubbert's estimated function was extremely sensitive to the data period used to estimate the parameters of the function, and regardless of the period used, was not as good a predictor of supply as a casual glance at Figure 6(a) might suggest. The solid line is a Hubbert curve estimated using a 1900-1993 dataset. At a glance it appears to fit the production data well, at least for the period as a whole.

However, if we focus in on the recent past, as seen in Figure 6(b), it is clear that actual supply has deviated quite far from the Hubbert curve in recent years. By 1993, the estimated Lower 48 supply using the Hubbert methodology was nearly 30% below actual production, and the underestimation appeared to be systematically growing.

Figure 6. The Hubbert Curve



But this still overstates the predictive power of the Hubbert approach. That is, the exercise above considers the performance of the function in fitting the data ex-post to the full set of data available today. Of course, this is not a reasonable analog to the task of a forecaster in, say 1970. Rather, he was faced with estimating, ex ante, supply in the next 25 years, obviously a more formidable task.

[41] Although even then, the Crude Oil Windfall Profits Tax held the net value at the wellhead substantially lower than world market prices.

Hubbert's estimates were initially ridiculed by industry[42], government, and academics, who saw it as a throwback to the traditionally conservative estimates that had consistently earned USGS ridicule since the 20's. In 1965, a Resources for the Future document called the data used by Hubbert "defective and ill-suited to producing valid projections...Mr. Hubbert's work with numbers and techniques appears to add nothing to the embryonic science of petroleumetrics.[43]" A Standard Oil economist in the same year commented that "it is unfortunate that the techniques used by Hubbert have given his conclusions an aura of mathematical accuracy that they do not deserve.[44]" But as the 60's wore on, and domestic oil reserves continued on a downward trend, Hubbert's own confidence in his conclusion increased, and the credibility of his critics eroded. In response to a barrage of professional criticism, he wrote in 1966 that "in any event, the question of the degree of validity of the conclusions in the Academy report are due to be settled unequivocally in the comparatively near future by the petroleum industry itself.[45]"

In fact the peak of U.S. domestic production occurred in 1970, almost precisely as Hubbert predicted. In retrospect, the Hubbert estimate of the peak year stands out as one of the most accurate projections in the history of the industry. In light of this experience, as actual production fell through the 70's, many of Hubbert's former critics raced to reduce their own estimates. Initially, there was a sharp downward revision in official USGS estimates to about half of their previous levels in the mid 70's, as shown in Table 3.

As a consequence, despite the long history of persistently ***conservative*** bias which had been so characteristic of official domestic resource estimates over the first century of the domestic industry, the principal perceived blunder of such estimates in the last quarter of a century has been precisely the opposite -- namely, one of ***overoptimism*** about domestic resource potential[46].

The usefulness of the Hubbert estimates for anticipating future domestic supply potential remains the subject of some controversy even today. There are those who view its accuracy as a lucky coincidence, similar to that of a broken clock that tells the right time twice a day. Others have attempted to provide it with some theoretical underpinning[47], others regard it still as a useful predictive device[48].

There are several reasons for skepticism. First, there is the lack of any theoretical justification, either geologically or economically, for the statistical function that Hubbert estimates[49]. Second, there is the question of its statistical reliability, since the estimated quantity of ultimately recoverable reserves has such a large band of uncertainty around it as to severely limit its usefulness. Third, the forecast implied by Hubbert's method predicts a symmetric production profile over the life of the resource, so that the buildup of production prior to the peak is a mirror image of production following the peak.

On the basis of the first 23 years of data following the peak, as shown in Figure 6(b), there have been significant deviations from that history, such as the stabilization and slow rise of Lower 48 production in the first half of the 80's, and the sharp slowdown in the rate of

[42] Not all of industry, however. Most notably, J. Moody of Mobil expressed stong support for the Hubbert view.

[43] Lovejoy and Homan [1965].

[44] See Ryan [1966].

[45] In "M. King Hubbert's Reply to J. M. Ryan" [1966].

[46] See, for example, "Oil and Gas Resources: Did USGS Gush too High?," *Science*, July 12, 1974.

[47] For example Kaufman [1991] and Cleveland and Kaufman [1991] attempt to reconcile the Hubbert appoach with an economic model by explaining the deviations of the actual production from the Hubbert estimate as attributable to price and regulatory factors. Their econometric results explain away most of the deviations from the curve for the period examined (1947 through 1985). However, it would appear that their results would also fail to explain the growing overstatement of the decline in production over the past decade, since the economic factors which they include have generally deteriorated in the past decade, suggesting that the deviation from the original Hubbert curve should overstate supply, which is the opposite of what has in fact occurred.

[48] See Smith and Lidsky [1992].

[49] Adelman [1995] points out that the logistic function typifies the product cycle of many goods, renewable or not. The production of mainframe computers, for example, seems to have followed the same pattern, which no one would suggest implied that the number of mainframe computers is somehow pre-ordained.

Table 3. Post-1974 Estimates of the Domestic Resource Base[50]

End of	Author	Cumulative Production	Identified Reserves[51]	Other Reserves[52]	Ultimate Resources[53]	Remaining Resources[54]
1974	USGS [1975]	100	62	50--127	212-289	112-189
1979	USGS [1981]	121	55	64--105	240-285	119-164
1986	USGS [1989]	147	51	33--70	231-268	84-121
1988	USDOE [1990]	153	60-78	25--35	238--266	85--113
1991	ORP [1992]	161	25	74--179	260--365	99--204
1992	USGS [1994]	164	51	35-72	244--277	80-113

Lower 48 decline since 1990. On a similar note, cumulative Lower 48 production through 1993 already exceeded the ultimate recovery initially estimated by Hubbert for all time.

As a consequence, while the prediction of a peak in U.S. production was a notable success, it does not follow that the path of declining production should necessarily bear any relationship to the pattern of production prior to the peak. In fact, Hubbert chose a sample period which fit his hypothesis well, but the choice of an alternate sample (1859 to present, for example) seriously reduces the goodness of fit of the logistic curve he uses. The addition of economic and regulatory variables helps considerably to improve the fit of estimates based on his method through 1985, but appears to be unable to capture the growing understatement of domestic supply that the method incurs in the last decade, or the growing geological optimism expressed in recent assessments of the United States resource base for the Lower 48 states.

Uncertainty in Recent Estimates

Since the mid-70's, most estimates of the ultimate recoverable domestic resource have explicitly recognized the uncertainties involved in the ultimately recoverable resource. While a portion of that uncertainty involves the volume of undiscovered resource waiting to be found, increasingly there is a recognition that economic, technological, and institutional factors are as great or even greater sources of uncertainty in assessing a mature producing area such as the United States.

Consequently, most recent studies have presented the estimates as a range or distribution rather than a point estimate. As seen in Table 3, current estimates of the ultimately recoverable domestic resource base by the Oil Resources Panel (ORP[1992]) are between 263 and 368 billion barrels, of which we have already consumed about 164 billion barrels. This would leave a domestic resource base of between 99 and 204 billion barrels, which would support production at recent levels for 38 to 78 years. Recent estimates by the USGS, assuming current technology, have a high range estimate nearly 100 billion barrels lower[55].

[50] An additional study was completed by USGS in January 1995, but it was not directly comparable to others cited insofar as it was limited to an assessment of onshore and state waters only. Assessments of the federal Outer Continental Shelf were not available at the time of this writing.

[51] Except for the ORP[1992] study, includes all identified recoverable reserves, proven or not. The ORP[1992] study includes only proven reserves.

[52] In all studies, includes estimates of undiscovered recoverable resources. In the ORP[1992] study also includes identified but unproven resources.

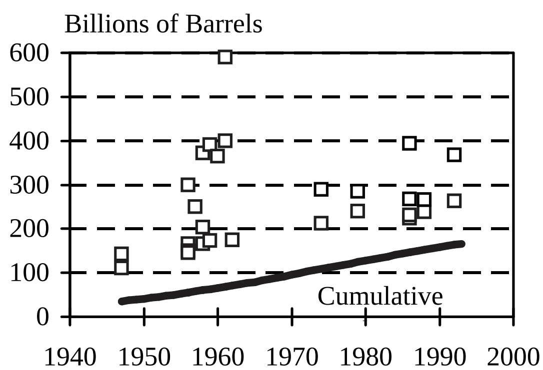
[53] Ultimate resources corresponds to the sum of (A) through (D) in Figure 5, above. Consequently, it is contingent on economics and technology available as of the date of the estimate, and it is not an absolute ceiling, insofar as changing economics and technical progress could capture at least a portion of boxes (E) and (F).

[54] Remaining resources is the estimated volume of ultimate recoverable resources less cumulative production up to the date of estimate.

[55] It should be noted, however, that the ranges presented in Table 3 are only suggestive, not precise. Among other things, the meanings of the ranges across studies differs. The USGS estimates are an explicitly probabilistic range intended to capture 90% of the possible volumes of undiscovered recoverable resources. The DOE and ORP estimates reflect other variables as well, notably technology, price, and land access.

It is worth noting, however, the extreme uncertainty revealed by the width of this range. The studies done in the past decade suggest that the remaining resource to be utilized depends critically on the course of technology, prices, and land access over the next several decades. Depending on such factors, recent studies suggest that the ultimate volumes of domestic crude oil recovered could be more than double the early estimates made by Hubbert, but are not expected to reach more than half to two thirds the most optimistic of the estimates prepared in the 60's. Figure 7 summarizes the history of estimates of the domestic recoverable resource base.

Figure 7. Cumulative U.S. Oil Production and Estimated Total Oil Resources



At a minimum, the behavior of domestic supply over the past decade and a half demonstrates that the simple deterministic supply mechanism at the heart of the Hubbert analysis does not capture key features of post-peak U.S. supply behavior. In particular, post-peak supply deterioration has been far slower than pre-peak growth. Nonetheless, it also indicates that supply from a mature area cannot grow without bounds. Substantial technical progress and drilling effort are expected to be required to push ultimate recovery even to levels as high as half to two thirds the size of the most optimistic estimates prepared in the sixties. Moreover, there are often very significant lags involved in developing new sources[56], particularly offshore or in remote areas on land, so that development of incremental supply ten years hence requires near term investment in exploration, development, and sometime transportation.

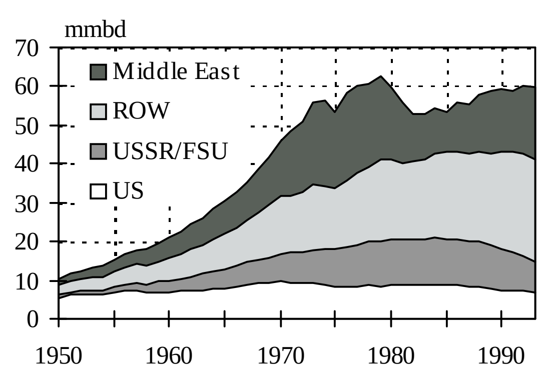
Estimating World Oil Resources

There are lessons to be learned from the U.S. experience with implications for world supply. However, the experience has also been frequently and easily misinterpreted. Perhaps the most common misinterpretation, rampant in the seventies, was the notion that the peak and decline of Lower 48 oil production was a bellwether of global resource scarcity.

Worldwide, as was seen in Figure 1, crude oil production rose rapidly in the post-World War II period, reaching a peak of about 62 million barrels per day in 1979, fueled principally by the growth in supply from the Middle East countries, as seen in Figure 8.

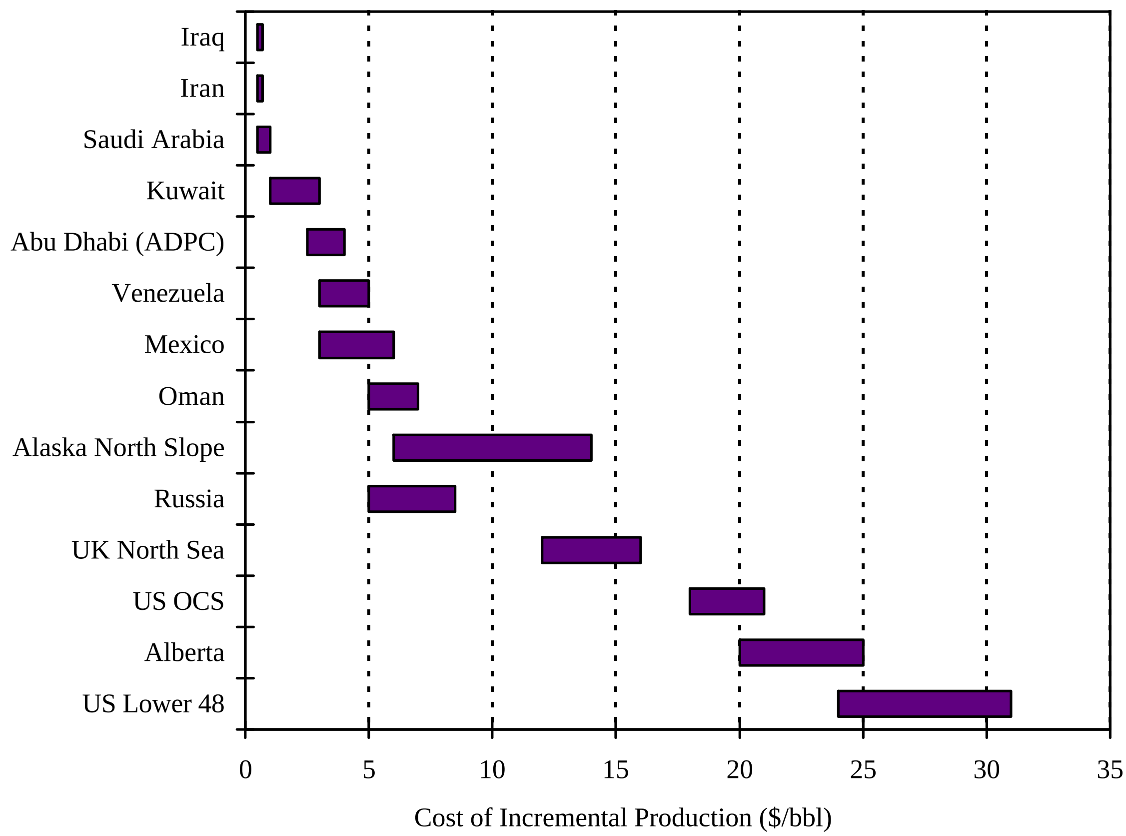
In 1950, the US accounted for about a third of world proven reserves and about half of worldwide production. By 1993, the US accounted for less than 3% of global reserves and only about 12% of production. These changes were the result of rapid demand growth in the industrial economies, satisfied by rapid supply growth, first by OPEC countries during the 60's, later by rapid non-OPEC supply growth in the 80's and 90's.

Figure 8. Crude Oil Production by Region, 1950-1993



[56] Prudhoe Bay, for instance, took almost exactly a decade from discovery to production. Similarly, the North Sea took decades to develop. Estimates for development of the Arctiic National Wildlife Range anticipate more than a decade between leasing and production. Such lags are more the rule than the exception.

Figure 9. Worldwide Incremental Production Costs



Source: Stauffer [1994]

Most of the reserves from the new producing areas were added after the US industry had passed its centennial. The principal consequence of this "age difference" between the U.S. Lower 48 and much of the rest of the world manifests itself in relative costs of incremental production[57]. The absolute magnitudes of these numbers are highly speculative, of course. Nonetheless, a number of alternate measures are available from both company data and trade press compilations. The magnitudes and the rankings presented by Stauffer [1994], shown in Figure 9, appear plausible[58]. The low cost producers are generally the OPEC countries, particularly those in the Persian Gulf, while much of the U.S. resource base rests at the high end of the cost spectrum, particularly the Lower 48 onshore.

While the U.S. is still a major producer, the domestic Lower 48 onshore comprises a disproportionate share of the world's high cost marginal production. This high cost has been aggravated by serious institutional constraints on development of the two portions of the domestic resource base most competitive with imports, namely Alaska and the Federal OCS.

Far from being a representative bellwether of global industry trends, Lower 48 production

[57] These cost differences arise principally from the fact that the the drilling cost associated with a well of given depth is similar across areas, while the productivity of that well varies enormously, ranging from nearly 12000 b/d in Saudi Arabia to less than 12 barrels per day in the Lower 48 states.

[58] For a description of the methodology used to compute these costs, see Stauffer [1993, 1994].

has been a shrinking high cost outlier in the midst of a growing global market, with most of that global growth from sources 75 to 100 years younger than the bulk of domestic fields. The decline in U.S. supply after 1970 did not indicate that the U.S. was "running out" of oil, but rather that the costs associated with much of remaining Lower 48 resources was no longer competitive with imports from lower cost sources worldwide. Consequently, the decline in U.S. supply after 1970 represented not a signal of growing global resource scarcity, but rather a signal of growing global resource abundance.

In an unfettered global market, this cost structure would have caused high cost U.S. production to decline, and imports and lower cost domestic supplies to increase. In fact, this was happening in the early 70's (prior to the 1973 Arab embargo), and in the past decade, both periods in which U.S. production was declining as non-US production was growing. But for an extended period between those years, from the mid 70's until the mid 80's, global supply behavior was so heavily dominated by market intervention by both the U.S. and OPEC[59] that these trends were heavily masked or even reversed. During that period, the downturn in U.S. supply was often interpreted as merely symptomatic of impending global resource exhaustion[60].

In fact, the loss of supply and the corresponding rise in price were attributable to a number of transitory factors. First, the Arab embargo of 1973 and subsequent OPEC restrictions on supply shocked portions of the world economy into recessions that reduced demand for petroleum products. Second, the U.S. intervened to "protect" its domestic economy via a regulatory intervention that discouraged domestic oil supply throughout the 70's, and to a lesser degree, the early 80's. Third, at the end of the 70's there was a loss of Iranian and Iraqi output resulting from disruptions associated with the Iranian revolution and the subsequent Iran/Iraq war. Fourth, and of longer run consequence, was the commitment of Saudi Arabia to sustain the higher prices by acting as "swing producer," willing to defend the official price by swinging its output down if prices fell below the target price, and up as prices rose. The result was a global supply pattern that appeared to have peaked in 1979 or 1980, and which contributed to a perception of global scarcity. In fact, there *was* a global *supply* scarcity, contrived by OPEC country policies and aggravated by misguided U.S. policy responses, with little or no relation to actual global *resource* scarcity[61].

Through the 80's, these policies were progressively removed, as the U.S. abandoned price controls and the Windfall Profits Tax, and Saudi Arabia eventually repudiated its commitment to act as OPEC's swing producer[62,63]. Prices fell, worldwide demand growth resumed, and the most marginal production in the world, that of the Lower 48 onshore, took the brunt of the loss in market regained by low cost Gulf producers[64]. While worldwide production leveled in the early 90's with the slowdown in OECD economic activity, recently demand has begun growing again, and worldwide production is expected to surpass its 1979 peak within the next two years[65].

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[59] More correctly, by individual OPEC member countries, in particularly Saudi Arabia.

[60] For example, Meadows, D. et al. [1972].

[61] Except, that is, to the extent that differing resource potentials motivated each country's policies toward supply growth and pricing strategy.

[62] Nazer [1986] clearly articulates the Saudi repudiation of its previous swing producer policy. As a consequence of this strategy, the Gulf states did recapture nearly 10% of the petroleum market from 1985 to 1993, but after nearly a decade were still far short of the share they controlled in the early 70's. Many of the losses proved to be permanent or at least long term, as oil was backed out of many traditional uses in favor of other fuels, such as coal, natural gas, and (in some countries) nuclear power. Moreover, many of the new non-OPEC supply sources continued to expand even at the lower post-85 prices, at rates troubling to OPEC. By 1994, for instance, despite sharp declines in real prices, OPEC output was relatively stagnant as non-OPEC supply grows rapidly enough to absorb most of the increase in world demand. As if this were not enough, OPEC producers are still faced with the prospect of absorbing the return of Iraq to export markets at some point.

[63] Gately [1994] shows that continuation of this market share strategy dominates any return to swing producer policy from the standpoint of maximizing the present value of revenues to the major Gulf producers countries over a wide range of market conditions.

[64] Although not evenly. Declines in US and FSU output masked the sustained growth in other non-OPEC output. See Stauffer [1994].

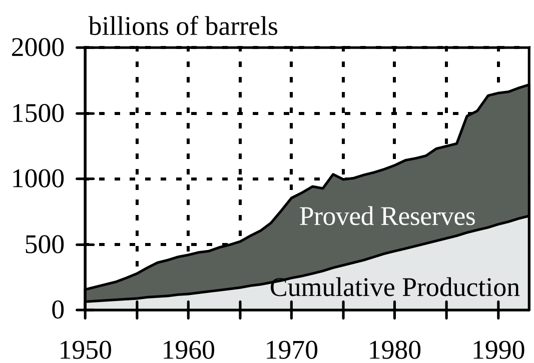
[65] See International Energy Agency [1994].

Proven Reserves: Apparent Increases in Worldwide Resource Abundance

As was seen in Figure 1, in 1950 the world had already produced over 60 billion barrels of crude oil, and was currently producing about 4 billion barrels per year. Proven reserves were about 90 billion barrels, enough to last about 22 years at then current production rates.

In the next 43 years, however, rapidly growing demand consumed not 90 billion barrels, but over 640 billion barrels. Perhaps even more remarkably, the reserves left at the end of the period were more than ten times the reserves estimated at the beginning of the period, as seen in Figure 10. Over those 43 years, gross additions to reserves had exceeded 1.6 trillion barrels.

Figure 10. Worldwide Cumulative Production and Proven Reserves



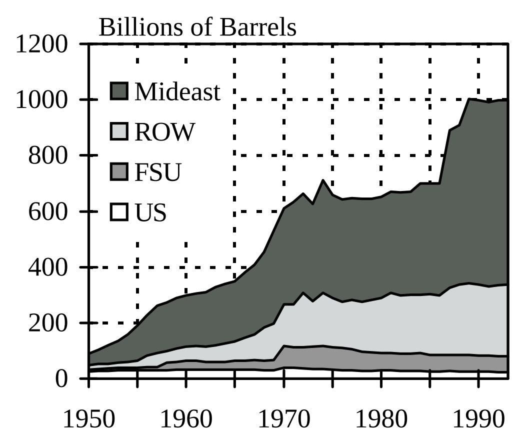
Consequently, the known "floor" on the ultimate recovery of world oil resources by the end of 1993 stood at over 1.7 billion barrels[66], about two thirds of which remained to be produced.

Whether viewed in terms of barrels or as years remaining at current production rates, there was a massive increase in worldwide proven reserves of crude oil in the post-WWII period. By the end of 1993, proven reserves were sufficient to support production at 1993 rates for more than another 45 years, more than double the estimates of the late 40's.

Are Published Reserve Estimates Reliable Signals of Resource Abundance?

However, the growing abundance suggested by the proven reserve estimates may be distorted. It is well known that despite long-standing attempts to standardize resource classification schemes across countries, actual measurements vary significantly[67]. The definition of proven reserves in the U.S. is quite narrow by world standards; that used in the Persian Gulf, for instance, is, by at least some interpretations, quite liberal. Moreover, we know that the bulk of the massive increase in world oil reserves since 1985 was overwhelmingly the result not of a surge in global drilling activity, but rather of several discrete huge revisions, by each of the major Gulf countries since 1985. If we separate out world reserve additions by region, as shown in Figure 11, it is clear that apart from those Middle East revisions in the late 80's, world proven reserves have been little changed since the early 70's.

Figure 11. World Proven Reserves of Crude Oil (billions of barrels)



The 300 billion barrel ***revision*** in the Middle East in the late 80's roughly equaled the ***total*** reserves of the world outside of the Middle East. Possibly, these revisions were more reflective of political gamesmanship in OPEC quota allocations than of expanding resource

[66] The sum of 700 billion barrels already produced and 1 trillion barrels in proven reserves.

[67] See SPE [1993], Roger, J.et al [1994]

Table 4. Estimates of the World Oil Resource Base, 1920-1994 (billions of barrels)

End of	Author	Cumulative Production	Remaining Reserves	Ultimate Resources
1919	White [1920]	8	35	43
1942	Pratt et al. [1942]	42	558	600
1946	Duce	52	348	400
1946	Pogue	52	503	555
1948	Weeks	58	552	610
1949	Levorsen	62	1438	1500
1949	Weeks	62	948	1010
1953	Macnaughton	79	921	1000
1956	Hubbert	96	1154	1250
1956	Weeks [1958]	96	1082	1178
1958	Weeks [1960]	109	1891	2000
1965	Hendricks	172	2308	2480
1967	Ryman [1967]	197	1887	2090
1968	Shell	211	1589	1800
1968	Weeks	211	1989	2200
1969	Hubbert	226	1499	1725
1970	Moody	243	1557	1800
1971	Warman	261	1339	1600
1971	Weeks	261	2029	2290
1973	Moody, Esser [1974]	297	2000	2297
1975	Halbouty [1976]	339	1792	2128
1980	Masters et al. [1984]	448	774-2145	1222-2593
1984	Masters et al. [1987]	524	1076-1676	1600-2200
1989	Masters et al. [1991]	629	1371-2071	2000-2700
1992	Masters et al. [1994]	699	1401-2101	2100-2800
1994	Campbell [1995]	738	962	1700

supply or productive capacity[68]. On the other hand, the countries making these revisions in the late 80's (Iran, Iraq, Kuwait, Saudi Arabia, and the UAE) are some of the most prolific yet relatively unexplored areas of the world, so that it is also possible that these revisions simply offset previous understatements, particularly if the resource concept is broadened from proven reserves to include all "identified resources," proven or not.

[68] Campbell [1995a,b] argues that these "political" revisions were gross overstatements of Middle East potential (that only about 100 of 300 billion barrels added were legitimate), which along with several other criticisms, suggest that the USGS worldwide estimates of identified resources are too "optimistic."

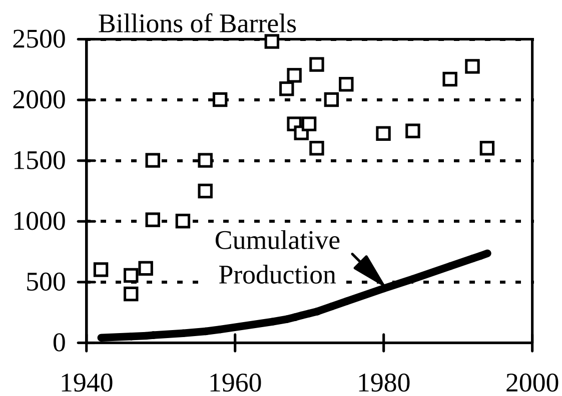
Broader Measures of World Oil Resources

While there are lingering doubts about this recent wave of revisions in proven reserve estimates, it should be remembered that conceptually, the size of the world oil resource base is far larger than proven reserves alone, so that addressing the long run supply potential clearly requires a broader measure. While a few estimates of worldwide resources were made prior to World War II, it was the rapid growth of worldwide consumption during and after the war and new concerns about worldwide exhaustion that led to a number of new estimates after the war. Several of these are shown in Table 4.

The estimates of world resources rose rapidly with production until the early 60's, reaching a maximum of 2.5 trillion barrels by the late 60's. After 1970, estimates of the ceiling dropped, while production was accelerating, as seen in Figure 12.

More recently, there have been a series of papers presented at the last several World Petroleum Congresses assessing world oil resources. The last four such papers have been prepared in a consistent format[69] by the USGS[70].

Figure 12. Estimates of World Crude Oil Resources



One important feature of these USGS assessments has been an attempt to standardize known resources (proven and probable reserves) in such a way as to retain comparability across countries. Their first assessment in 1983 estimated ultimate recoverable resources at 1.7 billion barrels, while the most recent estimate in 1994 puts the ceiling at 2.3 trillion barrels[71] (although with a band of uncertainty between 2.1 and 2.8 trillion[72]), of which 700 billion barrels have already been produced. Consequently, USGS estimates that between 1.4 and 2.1 trillion barrels remain to be produced worldwide, which would sustain current rates of world consumption from 63 to 95 years. Importantly, this assumes that between 4.1 and 5.4 trillion barrels are left in the ground as unrecoverable[73]. Technical change could extend this lifetime by between 60 and 80 billion barrels (3 to 4 years) for every 1% increase in average worldwide recovery efficiency.

The Campbell Dissent: a New Hubbert?

The recent USGS estimates that worldwide conventional oil resources will eventually reach the 2 trillion barrel level, plus or minus 10% or so, has been characterized as the consensus geological view in place for nearly three decades. It is a number large enough to be consistent with plentiful current supplies, but small enough to imply a peak in world supply early in the next century with even modest demand growth (this point is elaborated on more in the next chapter). In short, it is a number consistent with the simultaneous observation of growing abundance and the expectation of scarcity imminent within a generation or so that motivated this study.

But much as Hubbert challenged the developing consensus of abundance regarding U.S. domestic resources in the 60's, and suggested an imminent decline in a very short time, another respected geologist has in recent years been touting a similar global theme for the 1990's. Looking primarily at the same data utilized by the USGS[74], Campbell foresees an imminent decline in global supply of conventional oil within the next *five years.* His projections are somewhat alarmist, insofar as he sees such a peak as giving rise to "radical change in the world's economy with colossal political consequences. [Yet] the laws of supply and demand ... are seemingly ill-prepared to address the depletion of the energy source upon

[69] At least the crude oil estimates are consistent. Natural gas liquids, natural gas, and unconventional resources have been treated differently each Congress, sometimes included in the USGS study, other times the subject of a separate report.

[70] See Masters et al. [1983,1987,1990,1994].

[71] The 2.3 trillion corresponds to the mode of the estimated lognormal distribution.

[72] That is, there is estimated to be a 95% chance that ultimate recovery reaches the lower bound, and a 5% chance that it exceeds the higher bound.

[73] Assuming an average recovery efficiency of 34% of original oil in place.

[74] Campbell is with the consultancy of Petroconsultants, S.A. in Geneva, whose database on world drilling, reserves and production was used as a principal input into the USGS analysis as well.

which so much of the world's economic experience has been based.[75] "

The heart of Campbell's critique is that (a) published proven reserve estimates have become progressively politicized to a degree as to not be reliable, (b) that the Delphic surveys used by the USGS are notoriously unreliable, possibly also politically motivated[76], and in particular do not reflect (c) that the major 300 billion barrel recent revisions by Middle East producers may be overstated by as much as 200 billion barrels.

Campbell portrays his point estimates as significantly different from the USGS World Petroleum Congress estimates. In fact, they are very different (nearly 20% below the lower bound of the USGS estimate of ultimate recovery), but not so different as to change the estimated world production peak by more than a decade. As will be seen later, to substantially change the outlook requires some multiple of the 2 trillion barrel estimate of ultimate recovery. There are two potential sources of such multiples -- currently unrecoverable resources at known sites, and second, alternative sources of currently unconventional liquid hydrocarbon resources.

Increased Recovery Efficiency for Conventional Oil

As described earlier, current production methods on average are thought to typically recover only about a third of the oil in place. Based on such a rate, the recent estimates of ultimate recovery in the 2.1 to 2.8 trillion barrel range are premised on a total original oil in place worldwide of 6 to 8 trillion barrels, of which 4.1 to 5.4 trillion barrels worldwide will be left unrecovered[77].

This may not be plausible. Many new developments have recovery efficiencies[78] in excess of 50%. North Sea operators now routinely aim for 50% recovery, or even more, and some North American onshore operations have achieved recovery rates in excess of 70%. This has two implications for future oil supply.

First, in the case of newly identified resources, there are larger reserve estimates associated with a given volume of oil in place, since the higher recovery rates are part of the original development plan of a new field. As these new supplies with higher than average recoveries are developed, these sources will pull up aggregate recovery efficiency directly. Second, the diffusion of technology raises the recovery efficiency at old, known locations, as application of new methods recovers volumes not previously thought to be recoverable. In mature areas such as the U.S., Canada, and Russia, the additions from new sources are typically small relative to even small sustained increases in recovery rates at old fields. This follows primarily from the fact that the old

[75] Campbell [1994].

[76] There is also an assertion that "economists" are biased toward estimating larger numbers, although the motivation for such bias is not specified. While the record suggests strongly that a bias existed, the evidence is overwhelming that it was in the opposite direction. One of the most serious errors made consistently by energy economists over the past two decades has been one of grossly *underestimating* supply. This record has been thoroughly examined by Lynch [1992], the Stanford Energy Modeling Forum [1992] and Huntington [1993]. It reveals two things -- first, a pathetic price forecast record across all models, driven in large part by consistent underestimation of supply, across a wide spectrum of models used by government, industry and academics in the late 70's, and second, strong evidence that models based on depletion of fixed, geologically based estimates of resource potential produced systematically poorer estimates of supply than those econometrically based on observed supply behavior without regard to such a constraint. A very small handful of economists challenged these "fixed resource assumptions," not on grounds that such resource constraints did not exist, but rather on grounds that they were not likely to ever be binding in a global sense, and consequently were likely to be empirically irrelevant. In a response to Campbell, Adelman [1995] argues that Campbell puts undue emphasis on the reserves estimates as indicators of long run supply, and neglects the effects of technology and learning on future potential. Moreover, he points out that Mr. Campbell's consultancy presented a similar analysis in 1986, demonstrating that a decline in non-OPEC output was "imminent and unstoppable ... well before the end of the decade." In fact, non-OPEC production, outside of the US and the FSU, ***rose*** by over 6 mmbd from 1986 until 1995.

[77] It may appear surprising, given the magnitude of resources involved, that such casual approximations are used here. However, the imprecision is a necessity, made so by the lack of aggregate data on original oil in place. From 1966 until 1979, the API had collected such estimates as part of its annual reserve assessment. When DoE assumed the task of collecting reserve statistics, that series was abandoned.

[78] Measured as the proportion of original oil in place actually thought to be recoverable.

fields are typically the largest fields. In the U.S, for instance, small changes from pre-World War II fields have for several decades accounted for the majority of Lower 48 reserve additions.

At this point, however, it should be noted that an increase in average recovery rates from recent levels of about 34% to 50% at some future point would yield 1.0 to 1.3 trillion barrels of crude oil worldwide[79], roughly doubling the remaining resource base of conventional crude oil. Of course, currently most of this resource is not economically or technically recoverable, but there are a number of positive signs that such growth might be feasible at some future date.

One such sign has been the development of newer exploration and drilling technologies, such as new 3D seismic techniques or horizontal drilling. The former allows for much greater ability to devise a drilling pattern to more fully drain complex reservoirs. The latter allows a single well to vastly increase its exposure to source rock, greatly increasing its recovery efficiency.

The second such sign is the sustained progress in the technology and economics of enhanced oil recovery (EOR). EOR methods currently include thermal recovery, chemical recovery, and miscible flooding. Thermal recovery is the most widely used technique currently, used in the recovery of heavy oil in relatively shallow reservoirs in California. Chemical techniques include a number of methods to alter the properties of the oil via injection of a number of chemical additives into the reservoir. Miscible flooding involves the mixing of commonly occurring gases, such as carbon dioxide, with the oil in place to greatly improve its mobility within the reservoir. Of the three methods, it is generally regarded as the one with greatest applicability to conventional oil in place in a wide variety of locations.

Despite the fact that most of the interest in EOR arose in the high price environment of the late 70's and early 80's, the growth in production has been resilient in the face of the decline in prices after 1986. While the number of EOR projects has declined sharply in the low price environment since 1986[80], the amount of production coming from those remaining projects has continued to grow. Even more encouraging is the fact that the most generally applicable method to the bulk of U.S. resources, miscible flooding, has also been the technology least affected by lower prices. Since 1986, such production has increased nearly fourfold, to about 300 thousand barrels per day in the U.S.

Unconventional Sources

Up to this point, the resources discussed consist primarily of conventional oil. It includes some enhanced oil recovery (EOR) from areas currently producing with such techniques[81], but it is primarily conventional recovery at current economic conditions. Some unconventional sources of oil are also well known, though not currently economically or technologically viable on a large scale.

The principal resources included here are oil shale in the Western United States, heavy and extra heavy oil such as that found in Venezuela, and bitumen (natural tar) such as found in Alberta. Table 5 presents estimates of such resources. Together, the volumes of such resources approach 15 trillion barrels, nearly an order of magnitude greater than current estimates of remaining recoverable conventional resources.

Again, actual experience provides strong reasons for optimism in this area. In Alberta, for instance, there have been major cost reductions in the past several years due to advances in mining and transportation. Operators have already cut production costs to $11 per barrel, and expect to be producing at $9 per barrel by the turn of the century. Some estimates of the economically recoverable

[79] Based on a total worldwide estimate of 6 to 8 trillion barrels of original oil in place.

[80] The number of projects in the U.S. has fallen by more than 50% since 1985, while production in 1992 was nearly 800,000 barrels per day, 2.3 times that of 1980.

[81] Some heavy oil produced with enhanced recovery (EOR) techniques.is included. Currently, this accounts for about 10% of production in the US and about 13% of production in Canada. While lower prices since 1986 have sharply reduced the number of EOR projects, total EOR production continues to grow (Stosur et al. [1994]).

Table 5. Known Unconventional Crude Oil Resources[84]
(billions of barrels)

Source	United States	Non-U.S.	World
Heavy & Extra Heavy Oil	31	574	605
Recoverable Bitumen	7	429	436
Shale Oil	5600	8283	13883
Total Unconventional	5638	9286	14924

portion of Alberta's tar sands have recently been as high as 300 billion barrels[82].

In addition to these potential nonconventional sources of known petroleum resources, other even more exotic fossil fuel resources are known, though not yet reliably quantified. Gas hydrates, for instance, consist of crystallized natural gas and water under high pressure, such as found beneath oceans and Arctic permafrost. Such unconventional fossil fuel deposits are estimated to contain as much energy as all other fossil fuel combined. While currently too costly to warrant production, future development of such resources could conceivably increase available fossil fuels by more than an order of magnitude beyond the volumes of conventional oil resources discussed here[83].

Summary: Estimates of Resource Constraints

The above survey paints a bleak picture of remaining resource potential only if we constrain our view to the narrowest portion of that resource base, that of proven reserves. Even pessimistic views of those conventional oil resources approach a trillion barrels, about 45 additional years at current production rates. Conventional oil resources yet to be discovered, according to recent estimates, may stretch this by 60 to 100%. Raising average recovery from current levels of about a third of original oil in place to about 50% at some point far in the future via EOR and other technological improvements could add another 1 to 1.3 trillion barrels of conventional oil. Unconventional resources might provide another 1 or more trillion barrels from promising techniques applied to heavy and extra heavy oil in Alberta and Venezuela.

Apart from these conventional resources and demonstrated potential resources, there are a number of more exotic possibilities[85]. A technical breakthrough in the production of shale oil could add another 14 trillion barrels. Advanced EOR techniques not yet demonstrated, or even more exotic resources, like gas hydrates, could dwarf even that breakthrough. None of these are yet viable, but over the course of several decades to a century, it would be surprising and unprecedented if some new technical breakthrough not currently anticipated did not arise.

[82] See Symonds [1995] for a recent summary of industry experience in Alberta.

[83] Japan is now planning a project to mine such resources from beneath the Sea of Japan by 1999. See "Going Down: Japan Invests in an Alternative Source of Energy," *Scientific American*, August 1995, pp.36-37.

[84] From Masters et al. [1991].

[85] Such as microbial techniques, radio frequency (RF) heating, downhole steam generation, and a number of others. See Stosur [1994].

Chapter 3.
Supply as if Only Geology Mattered

"If [petroleum] is not there to begin with, all the human ingenuity that can be mustered into the service of exploration cannot put it there... The literature of the past decade suggests that the best place to look for oil would be in the economics departments of American universities and research institutes, ... not in sedimentary rocks."

-- Richard Nehring, 1981

"...Higher [resource] numbers are likely to be quoted and used by economists and others lacking insight into the matter..."

-- C.J. Campbell, 1994

Of Course Geology Matters

The above quotes give the flavor of a long standing tension between geologists and economists in gauging future oil resource availability. From the geological perspective, economists have often been accused of treating too lightly the constraints imposed by nature. From an economic perspective, geological estimates have often been characterized as too rigid, often seriously underestimating the potential of those volumes to change in response to prices and technology[86].

While not completely ignoring these conflicting perspectives, this chapter is not addressed at resolving them. Rather, the task of this chapter is to examine the several most recent geological assessments of world oil resources, the dynamics of petroleum resource development implied by them, and the uncertainties and limitations acknowledged by the authors of those assessments.

The assessments to be examined are those prepared by the US Geological Survey for the last four World Petroleum Congresses[87], beginning with the 11th Congress in 1982, and ending with the assessment at the 14th Congress in 1994. Not only are these the most recent and probably most widely publicized assessments, but they offer a number of very strong advantages over other available estimates.

First, with respect to identified resources, they have been carefully assembled in a consistent manner across countries and across time using the most detailed and authoritative field level data[88] available at the time of each estimate. This both avoids some of the major problems of cross country comparability mentioned earlier with respect to proven reserve statistics[89], and allows for an examination of the dynamics of world oil resource development over a period of 12 years, during which average real crude oil prices in the world declined to about half of their level in 1980.

Second, in these assessments undiscovered resources are estimated not as a single point, but as a probability distribution which captures the uncertainty, or at least some of the

[86] Of course, these are somewhat extreme views. Many of the most significant contributions to an understanding of the supply process has been done jointly by geologists and economists.

[87] Previous world resource assessments were produced for earlier Congresses, going back at least to the sixth Congress, in 1962. Each of these earlier assessments, however, were prepared by different individuals, who often changed the scope of their coverage in a manner that complicates comparability of the estimates.

[88] The USGS authors use field data from Petroconsultants worldwide databases, combined with independent information generated by USGS and the Department of Energy's Foreign Energy Supply Assessment Program.

[89] As well as some other less significant problems such as inclusion of some natural gas liquids in oil reserve estimates in some countries.

Table 6. USGS Estimate of World Conventional Crude Oil Resource Volumes[91], 1/1/93
(Billions of barrels, except as noted)

	Ultimate Recovery	Cumulative Production	Identified Resource	Undiscovered Resources[92]	Remaining Resource
World	2385	699	1103	583	1686
United States	259	164	51	44	95
USSR/FSU	375	119	125	131	256
Middle East	923	185	597	141	738
Other	827	231	330	266	596
OPEC	1176	283	706	187	893
Non-OPEC	1209	416	397	396	793
Mideast Share	38.7%	26.5%	54.1%	24.2%	43.8%
OPEC Share	49.3%	40.5%	64.0%	32.1%	53.0%

uncertainty inherent in such estimates. While there are a number of well known potential difficulties with subjective estimates of this type[90], even by professionals accustomed to working routinely with the quantification of uncertainty, the representation used by USGS does capture a band of uncertainty that provides users of the estimates with at least some basis to judge the precision of the estimates as perceived by the estimators themselves.

While some challenges to the value of such estimates have been made by both economists and geologists on the basis of the history outlined earlier, we will not focus here on those criticisms[93]. There are sound reasons to expect that recent estimates *are* more reliable than those of a few decades ago.

Clearly, new geophysical imaging technologies allow for more precise location and characterization of the resource base. New drilling materials, equipment and methods allow for far more flexible access to complicated geologic structures[94]. Perhaps most importantly, far more of the potential areas for new petroleum discoveries have now been explored, although major areas of the earth still remain lightly explored[95]. USGS, not implausibly, argues that they now have greater theoretical understanding of the geologic factors which give rise to oil occurrence, and that this understanding precludes the need for extensive exploration of large parts of the globe which they regard as unfavorable to occurrence of oil[96]. Finally, unlike the earlier estimates that occurred in periods of growing worldwide

[90] See Capen [1976], who documents several interesting experiments that suggest a consistent tendency among experts to overestimate the precision of their knowledge in areas of their expertise.

[91] Remaining resources here comprise identified resources (proven and probable reserves, plus undiscovered recoverable resources).

[92] Mean estimate

[93] The criticisms are both that the estimates are far too optimistic, primarily due to taking recent revisions in the Persian Gulf on their face value, or near it (see Campbell [1995]) to the other extreme that the estimates are made far too low due to their heavy discounting of the effects of technology and learning (see Adelman's [1995] response to Campbell, and Odell [1994])

[94] See Wollstadt [1992] for a discussion of these technologies.

[95] The significance of this relatively light exploration intensity is subject to dispute. Grossling [1975] cites this difference in exploration intensity as evidence of large remaining resource potential. The "Realms hypothesis" (see above) suggests that such relative drilling intensities are of little consequence to large areas of the globe.

[96] However, there remains no technique other than actual drilling of a prospective geological target that is capable of establishing without doubt the existence of oil at *any* particular location.

Table 7. Estimates of Remaining Conventional Crude Oil Resource Volumes, 1/1/93 (Billions of Barrels, except as noted)

	Proven Reserves (OGJ)	Identified Resources (USGS)	Undiscovered Reserves (USGS)	Remaining Resources (USGS)
World	999	1103	583	1685
United States	25	51	44	95
USSR/FSU	57	125	131	256
Middle East	662	597	141	738
N. America (exc US)	57	61	64	125
S. America	72	78	56	134
Europe	16	43	24	67
Africa	62	77	51	128
Asia/Pacific	41	71	71	142
OPEC	772	706	187	893
Non-OPEC	227	397	396	793
Mideast Share	66.3%	54.1%	24.2%	43.8%
OPEC Share	77.2%	64.0%	32.1%	53.0%

discoveries, the current estimates occur against a background of a long dearth of new discoveries of giant fields worldwide.

The present exercise takes the geologic assessments of USGS as given (including their acknowledged uncertainties and limitations). The task of this chapter is to examine the implications of these assessments as a potential constraint on future world oil supply, and the robustness of these implications to the uncertainties and limitations recognized explicitly by the authors of these resource assessments.

The 1994 USGS Assessment

Table 6, above, summarizes the latest USGS assessment, as presented to the 1994 World Petroleum Congress[97]. As of the beginning of 1993, USGS estimates that the volume of conventional oil worldwide that will eventually be recovered amounts to about 2.4 trillion barrels, of which nearly 700 billion barrels have already been produced. At 1993 production rates of about 22 billion barrels annually, this remaining 1.7 trillion barrels would support 1993 production rates for another 76 years.

Several features of this estimate of remaining resources are worth noting. Most importantly, it is nearly 70% higher than the more commonly cited proven reserve numbers available in the trade press, which were shown in Figure 2, above. This reflects two factors. First, it reflects the fact that identified resources in the USGS estimates are not equivalent to trade press estimates of proven reserves. Second, it reflects a broader resource concept than reserves, since it includes estimates of resources yet to be discovered.

As seen in the more regionally detailed Table 7, the worldwide identified resources estimated by USGS are about 11% higher than reported proven reserves, although the differences are far greater for individual areas. This reflects the USGS identified resource definition, being broader than most estimates of proven reserves, by inclusion of probable reserves, yet somewhat

[97] See Masters et al. [1994].

Figure 13. USGS 1994 World Resource Assessment by Resource Category (billions of barrels)

<table>
<tr><td>(A)
Cumulative
Production
699</td><td>(B) + (C)
Identified Reserves
1103</td><td>(D)
Undiscovered Reserves[98]
582</td></tr>
<tr><td colspan="2">(E)
Subeconomic Oil in Place at Known Fields[99]
3498</td><td>(F)
Undiscovered
Subeconomic
1130</td></tr>
</table>

narrower than the official estimates reported in the Middle East.

In terms of the categories presented in Figure 4, these resources break down into the classification seen in Figure 13 above. Note that the remaining resource numbers presented in the above Table correspond to areas (B), (C) and (D) along the top row of the modified McKelvey box presented earlier.

That is, the estimates are static, in the sense of assuming fixed technology and economic conditions. As such, they capture future reserve growth from development at known fields (as resources move from (C) to (B)) as well as the expected additions from properties yet to be discovered (box (D)). However, they do not include any additions from volumes currently below the horizontal line (from boxes (E) and (F)), such as deepwater drilling beyond the reach of today's technology, or oil in deposits too small to be commercial given recent economics and current technology.

The most common inference drawn from the above numbers is that currently identified resources could sustain 1993 rates of production (22 billion barrels per year) for about 50 years, and new discoveries could extend that production for perhaps another 27 years. While such simple calculations provide an intuitively simple way to gauge potential resources, they can also be quite misleading, for two reasons -- the uncertainty surrounding the volume of undiscovered resources, and technical constraints on supply which preclude maintenance of constant production rates indefinitely.

A second inference often drawn from these numbers is that future supplies will be increasingly concentrated in OPEC, particularly in the Middle East, because nearly two thirds of identified resources are located there. This would appear likely, provided that those countries choose to develop those resources. Nonetheless, it should be noted that such increased supply concentration is not inevitable. Less than a third of undiscovered resources are in OPEC, leaving the non-OPEC countries with considerable supply development opportunities should OPEC choose to restrict its near term supply so as to substantially raise prices.

Uncertainty in the USGS Assessment

While presented as a point estimate in the above tables, the volume of undiscovered world resources remains highly uncertain. Moreover, USGS has gone to great lengths to quantify such uncertainty in their assessment of undiscovered

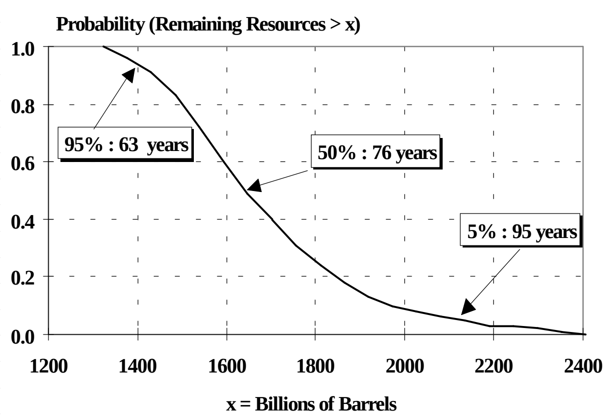
[98] Mean estimate.

[99] Both (E) and (F) calculated on basis of 34% recovery efficiency, implying a worldwide estimate of original oil in place of 7.012 trillion barrels.

oil, via accumulation of subjective probability distributions surrounding such volumes from experts in each of the areas assessed. While 583 billion barrels represent the expected value of potential discoveries, USGS presents its estimate of undiscovered oil as a probability distribution rather than simply as a point estimate.

Specifically, while USGS estimates that the expected value of remaining discoveries is about a 26 year supply at recent production levels, that estimate is extremely uncertain. A range capturing 90% of the possible volumes of undiscovered resources could be as low as 292 billion barrels (13 years) to as high as 1005 billion barrels (46 years). Added to identified resources, this implies that total worldwide remaining resources are as shown in Figure 14.

Figure 14. Uncertainty in USGS Estimate of Remaining World Oil Resources



That is, based solely on geological considerations contained explicitly in the USGS assessment[100], *there is a 95% chance that remaining resources are sufficient to sustain production at 1993 levels for 63 years, and a 5% chance that those resources would sustain production at the same rate for 96 years.*

To put the magnitude of this uncertainty into some perspective, this estimated range of more than 700 billion barrels between the high and the low case for the volume of remaining resources is about equal to the entire volume of cumulative production worldwide from the industry's birth in 1859 up to the beginning of 1993. More importantly, it should be emphasized that while this range is extremely large, it captures only one of several sources of potential uncertainties with regard to remaining resource volumes.

Two Implications for Future Markets

These simple transformations of resource volumes into years remaining at current production rates are useful as resource benchmarks, but too simplistic to offer much in the way of assessing future supply prospects. Typically, it is unlikely that a sustained constant level of output to the point of exhaustion or abandonment would be technically feasible. It is more likely that production would rise for a time, as discoveries outpace production and until the reserve to production ratio reaches a technically determined minimum, then decline gradually over a period of decades.

Above, resource potential has been discussed only in terms of volumes of recoverable oil in the ground. Translating these resource volumes into supply schedules requires incorporation of the technical constraints mentioned above. Of course, there are an infinite assortment of such constraints, requiring far greater information than that contained in the aggregate numbers available here. However, by representing the major constraints within a simple model, it is possible to vary those constraints over plausible ranges to identify trends which appear robust within those ranges.

For purposes of this exercise, a very simple model of discoveries and depletion was developed, using data drawn principally from the USGS assessment itself. The world was divided into four areas -- the United States, the Former Soviet Union, the OPEC countries, and the rest of the world. In each of the three non-OPEC regions, 5% of the current year remaining undiscovered resources is assumed to be discovered annually, and one-fifteenth of the

[100] Geologists with expertise in each region of the world were surveyed as to their own subjective probabilities regarding undiscovered recoverable resource volumes.

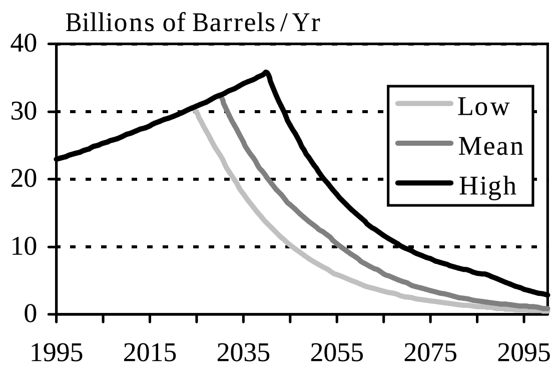
total identified resources are produced each year. OPEC production in the model is either the residual between an exogenously specified demand growth and non-OPEC supply, or the resource constrained maximum of one sixteenth of identified remaining resources, whichever is less. Very roughly, this approximates the model used by USGS in translating their worldwide resource potential into supply profiles.

The supply profile is assessed for three cases, corresponding to the mean, 5%, and 95% remaining resource levels[101] shown above in Figure 14. Two characteristic patterns appear in the implied supply profiles -- namely an imminence of the peak in conventional world crude oil supply, and an increase in the share of the market supplied by OPEC and the countries of the Middle East.

Imminence of Declining World Petroleum Supply

Figure 15 presents the world supply patterns implied by each of the three USGS remaining resource levels considered, given an underlying growth in world supply of 1% annually until reserve constraints become binding.

Figure 15. World Petroleum Supply, Three Resource Levels[102]



In the mean level resource case, supply grows to a peak of about 32 billion barrels annually (about 88 mmbd) in about 2030. In the low resource case, growth is sustainable at 1% until 2027, reaching a peak of 30 billion barrels annually (over 82 mmbd). In the high resource case, growth is sustainable for another decade and a half, when world production peaks at over 35 billion barrels (about 96 mmbd).

Each peak corresponds to the time at which the remaining crude oil resource base has shrunken to the point that it constrains further production growth. Of course, it should be emphasized that very simple, restrictive assumptions give rise to these profiles, which cannot be regarded as forecasts in any sense. Nonetheless, they are not implausible numbers, and they reveal several key supply characteristics implied by the USGS assessment; a peak level of world output about a third to two thirds above current levels, occurring sometime in the first half of the next century; followed by steep declines leading to the nearly complete demise of conventional oil supply as an energy source by the end of the twenty first century[103].

Future Interval of Increasing Supply Concentration by OPEC

A second characteristic of the supply profiles suggested by the 1994 USGS assessment is the likelihood of a resurgence of concentration of world oil supply in the OPEC countries, although the timing, magnitude and duration of the effect is highly sensitive to a plausible range of a number of key parameters. Figure 16 shows the trend in OPEC for the same three cases as examined above.

In all three cases, there is a long interval, beginning in the first half of the next century, during which OPEC rapidly recovers market share, reaching historic highs of nearly 70% of the world market in the first half of the 21st century. The rapid increase begins as early as about 2005 in the low resource case, is delayed until 2020 in the high resource case, and then spans one to two decades before reaching a peak of about 70% in all three cases. In all three

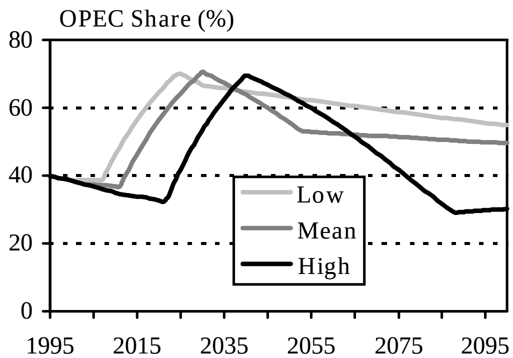
[101] Cooresponding to remaining resource volumes of 1.4, 1.7, and 2.1 trillion barrels, respectively.

[102] Assuming 1% growth in demand up to the point at which the minimum reserve to production ratio begins to constrain world supply.

[103] A sensitivity analysis showed these key characteristics are robust to reasonable ranges of variation in a number of the parameters used to develop these profiles (i.e., discovery rates, development rates, minimum reserve to production rates, and so on).

cases, OPEC's market share falls quickly after the peak, as increasing production depletes its resource base.

Figure 16. OPEC Share of World Petroleum Supply, Three Scenarios



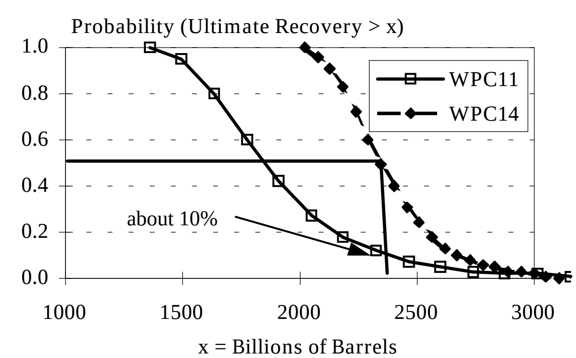
While the pattern of rise and decline in OPEC's share of the market is quite sensitive to assumptions regarding differential rates of regional supply growth, the long interval of resurgent growth in OPEC share is common to virtually all cases examined. Moreover, the assumptions behind Figure 16 incorporate fairly optimistic assessments regarding near term U.S. and FSU supply prospects, which implies that the OPEC share shown in the Figure are conservative[104].

One Caution: Surprises Have Already Occurred

While the above analysis consists entirely of a close examination of the implications of the USGS's 1994 assessment, and the uncertainty surrounding that assessment, it was mentioned earlier that one virtue of the assessment is the consistency of its methodology over time. The first assessment prepared by USGS appeared in 1982, in a format similar to that appearing in 1994. This span of a dozen years provides a short but very significant history from which to observe changes in perception of world oil resource potential. Table 8 presents these changes of estimates between 1982 and 1994.

As seen in the Table, over the 1982 to 1994 period, the world continued to at least identify new oil resources at a rate well above that depleted by production. Over 250 billion barrels were produced, but more than twice that was identified. Only in the United States did newly identified additions fail to replace production. Elsewhere newly identified resources were between 2 and 3 times the amount produced over the same period. Moreover, the source of the newly identified resources was *not* limited to the major revisions in the Middle East, discussed earlier. In fact, the 30% upward revision in the Middle East represented under half of the upward revision in identified resources worldwide. The most significant revisions in ultimate recovery[105], both in absolute terms and as a share of the initial estimate, was in the "other" category, principally in the non-OPEC countries other than the U.S. and the FSU, where resource potential was revised over 40% upward, by over 226 billion barrels. Also of interest is the fact that although uncertainty captured by USGS in its 1982 assessment admitted the *possibility* of upward revisions of such a magnitude, the possibility that ultimate resources could be as large as 2.3 trillion barrels was considered remote, as seen in Figure 17.

Figure 17. Comparison of USGS Assessments, 1982 and 1994



[104] This optimism, namely that U.S. and FSU supply in the early years remain flat, rather than continuing their recent decline rates, was retained to maintain comparability with the USGS assessment, not as a realistic estimate of supply prospects for either country.

[105] "Ultimate Recoverable Resources" as used here is defined as cumulative production plus identified reserves (whether proven or not) plus undiscovered recoverable resources.

Table 8. Changes in USGS Estimated World Petroleum Resources, 1982-1994
(billions of barrels, except as noted)

Region	Cumulative Production	Remaining Resources	Ultimate Recovery	Percent Change
United States	+40	-18	+22	+9.4%
FSU / USSR	+51	+48	+99	+40.4%
Middle East	+61	+145	+206	+29.7%
Other	+101	+125	+226	+41.2%
World	+254	+300	+554	+32.2%

The 1982 assessment indicated a belief among experts that there was only about a 10% probability that the ultimate resources recovered *for all time* might reach 2.3 trillion barrels. Within the considerably shorter period of the next 12 years, 2.3 trillion had become the new most likely estimate, despite an economic environment that had become considerably less favorable in 1994 than in 1982. It is obvious that the changes which have occurred in the 12 year period were largely unanticipated by USGS in 1982.

Clearly, this limited experience suggests that recent estimates be accompanied by a cautionary note. The estimates presented by USGS cannot be viewed with a great deal of precision, particularly when considering prospects over multiple decades. Over as short a time as 12 years, even in the context of a progressively deteriorating economic environment, and a scarcity of new giant fields worldwide, the expected resource potential had increased by about a third, an event dismissed as an outlier in work as little as 12 years earlier.

Implications of Geological Constraints for Supply

This chapter has summarized recent USGS world resource assessments, and attempted to flesh out the implications of that assessment for future world supplies. The cases considered above demonstrate that geological factors alone *do* imply *the imminence of depletion* in the first half of the twenty first century, followed by a period of sharp decline in later years, ultimately causing the industry to have nearly disappeared by the end of the twenty first century. Moreover, in all cases considered, there is a resurgence of OPEC supply concentration beginning early in the next century, lasting as long as several decades.

Both features of what was earlier characterized as the conventional wisdom -- sharp declines in worldwide production in the first half of the next decade, and sharply rising OPEC market share beginning in less than a decade -- are broadly consistent with the geological constraints suggested by the 1994 USGS assessment.

More significantly, perhaps, is the fact that these distinguishing characteristics of future world supply patterns are robust to changes in the level of remaining resources over a wide range. Nonetheless, even this wide range does not fully capture the uncertainties associated with world resources. It captures only the geologic portion of that uncertainty for a fixed technology and economic environment. We turn now to a consideration of such additional uncertainties.

Chapter 4.
Other Things That Matter: Economics, Technology, and Policy

> "Nature is inexhaustible and untiring; labor is a god which rejuvenates her."
>
> --Voltaire

> "Resources are not, they become; they evolve out of the triune interaction of nature, man, and culture, in which nature sets outer limits, but man and culture are largely responsible for the portion of physical totality that is made available for human use...The problem of resource adequacy for the ages to come will involve human wisdom more than limits set by nature."
>
> -- E.S. Zimmerman, *World Resources and Industries*, 1951

The previous chapter was largely expositional in nature, simply describing the geological viewpoint, and fleshing out the implications of the purely geologically based resource assessment for world supply of conventional oil. The treatment of uncertainty currently used by the USGS explicitly captures only that uncertainty associated with the volume of undiscovered resources. Even with this partial treatment, however, it was clear that the narrowness of the consensus of imminent exhaustion could be rejected, since even the uncertainties included by USGS allowed for a range of world supply possibilities inclusive of peak supplies anywhere from the first decade of the 21st century to the sixth decade or even later.

Limited Treatment of Uncertainty in Recent World Resource Assessments

In fact, however, there are a number of other well known uncertainties associated with the supply process which are only implicit in the USGS numbers, at best. For example, the identified reserves number is reported as a point estimate, although there are a number of uncertainties in that estimate attributable to technology, economics and policy.

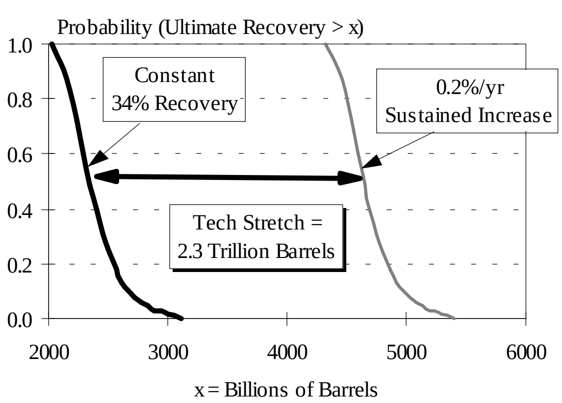
Changing resource economics, due either to changes in world prices or changes in finding or development cost, are not considered explicitly in the USGS framework. Similarly, policy considerations -- ranging from uncertainty of contract enforceability in the FSU to highly restricted access to the US offshore and Alaska, to international efforts to restrain growth of fossil fuel consumption, are not explicitly considered in the assessment, although all have the potential for overwhelming the sources of uncertainty that have been considered.

Apart from these considerations, however, which are clearly understood to be outside the scope of the current USGS method, there is another source of uncertainty that is at least implicit in USGS methodology, namely those innovations that produce reserve additions attributable to growth in average recovery rates. Particularly in mature producing regions such as the U.S. and the Former Soviet Union (FSU) these changes are likely to be a major part of the dynamics of resource accumulation. Note that in Figure 13 about two thirds of the original oil in place and nearly three quarters of the remaining oil in place is currently in the subeconomic category. Each 1% increase in average worldwide recovery adds from 60 to 80 billion barrels to the recoverable resource base. Changes in these recovery rates are very slow, but applied to such a broad resource base, small but sustained changes can easily be the major changes over a sufficiently long time horizon such as that considered here.

Sensitivity of Outlook to Technology

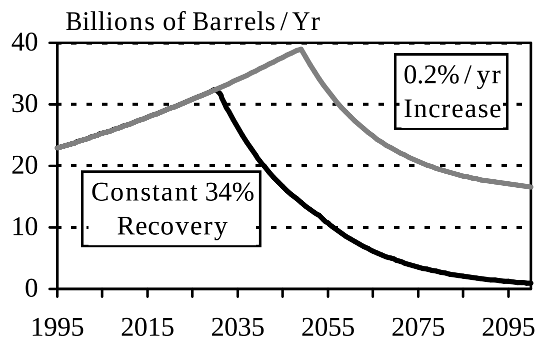
Considering this slow upward progression of recovery efficiency over time, Figure 18 presents the potential effect of small sustained improvements in recovery efficiency on ultimately recoverable worldwide resource volumes. As an example, a sustained two tenths of one percent annual growth in average recovery efficiency[106] would nearly double the mean level of remaining resources from the levels assessed by USGS, over the course of a century. It is this potential of "technological stretch" that has often led in the geologic literature to a characterization of technology as the "great multiplier".

Figure 18. Effect of Growing Recovery Efficiency on Remaining Resource Volumes



The impact of such small but sustained changes on altering the world oil supply outlook in a major way is shown in Figure 19. In the mean resource case, as was mentioned earlier, with no growth in recovery efficiency, world supply could reach a peak at about 32 billion barrels a year by the year 2030, after which steady decline would continue throughout the century. By the end of the century the industry would have nearly vanished. With slow but sustained improvement in recovery efficiency, peak output is not reached until 2049, at nearly 40 billion barrels per year, after which production declines far more slowly. Under this scenario, world oil supply by the end of the 21st century would be nearly 17 billion barrels per year.

Figure 19. Effect of Improved Recovery on World Oil Supply Profile[107]



The Dynamics of Resource Estimates

The hypothetical cases presented above suggest that failure to include future changes in average recovery rates is a rather severe limitation on estimates of resource potential, and that radically different supply outlooks would result from slow improvements in such factors as recovery efficiency. But is there any empirical evidence that such increases are plausible or likely?

This is a more difficult question than it appears, insofar as readily available data on reserve accumulation combines the reserve growth associated with both the extensive margin (new

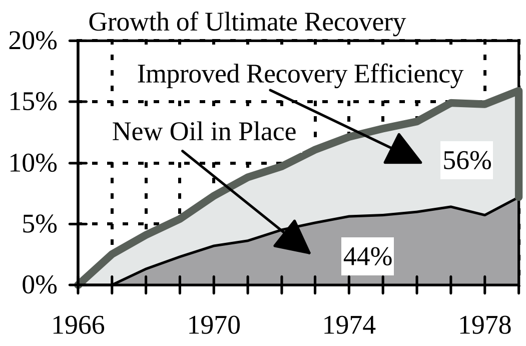
[106] Such an increase would raise average worldwide recovery from its current level of about 34% to about 56% by the end of the 21st century.

[107] The dark line represents the mean resource case above, the lighter line represents the same resource base with a 0.2% per year increase in recovery efficiency.

volumes of original oil in place), and the intensive margin (incremental reserves added via increased recovery rates from known properties). The former is clearly captured by the USGS methodology, the latter is not. To separate the two effects, in order to judge the potential significance of such an omission, one requires estimates of original oil in place and ultimate recovery for a fixed set of known resource occurrences. While API maintained such data for the U.S. from 1966 until 1979, no corresponding data has been maintained since that time. However, for those 14 years, a complete history of resource development is available.

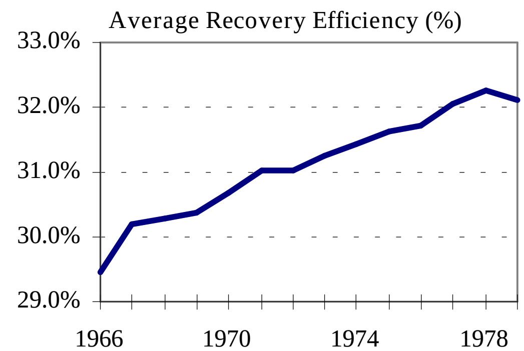
Over the period, 25 billion barrels of oil was added to ultimate recovery. Of that, over three fourths was from fields already known at the beginning of the period. New fields discovered after 1966 accounted for less than a fourth of the reserves added during the period. The 19 billion barrels added in known fields over the period was attributable to two factors -- growth of volumes of oil in place associated with delineation of field boundaries and more accurate measurement of other field characteristics, and more intensive utilization of those fields associated with improved recovery efficiency. Figure 20 breaks down the growth into these two factors, showing that well over half of the increase was associated with improved recovery rates over time.

Figure 20. Breakdown of Lower 48 Reserve Growth at Fields Discovered by 1966



At those fields, as shown in Figure 21, there was a very slow but sustained growth in average recovery rates at those fields discovered prior to 1967. Over the period, average recovery rates at those fields grew at an average annual rate of about 0.2% per year, within the range of the hypothetical cases presented above.

Figure 21. Average Recovery Efficiency by Year of Estimate, Lower 48 Fields Discovered by 1966



While this is obviously no guarantee that future improvements in recovery efficiency worldwide will be similar to the U.S. experience, the available evidence from the U.S. experience is in line with the range of hypothetical cases considered above. At even a 0.2% increase shown above.[108] the contribution of technical change to increase supply swamps the increases expected from new discoveries.

[108] There is a question of whether this growth from the older fields can continue over time.. No aggregate data is available to extend the range of Figure 20 to the present. However, there is evidence at the field level that such growth has continued. Lynch [1994] examines the recent growth of the largest fields in the U.S. examined by Nehring[1982], and finds continued growth over the past several decades, bringing estimates of ultimate recovery from those fields far above even the highest levels estimated by Nehring.

Chapter 5.
Is There Cause for Concern?

> "The diagnosis of the U.S. energy crisis is quite simple: demand for energy is increasing, while supplies of oil and natural gas are diminishing. Unless the U.S. makes a timely adjustment before world oil becomes very scarce and very expensive in the 1980's, the nation's economic security and the American way of life will be gravely endangered."
>
> -- *National Energy Program*, Executive Office of the President, 1977

> "...there is the common misconception that the world is running out of oil, that it will become more valuable over time and that one should take steps now to preserve it for future generations. [In fact,] oil is being discovered in large quantities and reserves continue to increase faster than consumption...Over the next three to four decades...supply will not be an issue...nor are we likely to see any upward trend in the prices of energy."
>
> -- Anthony Churchill, World Bank, 1993

> "A growing contradiction has arisen, on the one hand, between the expectations of what technology may achieve and, on the other, the political, economic, and logistic problems which limit the realization of these expectations."
>
> -- Bernardo Grossling, *Window on Oil*, 1975

Concerns Real and Imagined

As was described in the earlier chapters of this report, resource estimates and supply projections such as those described above have traditionally generated a great deal of public attention and concern, and have been utilized to justify a wide range of government policies. In particular, there are two concerns that typically have arisen -- one imaginary and the other real, usually in the context of a call for government corrective action of one sort or another.

In this chapter we examine these concerns, and the role of government in addressing them. In fact, there is almost certainly a role for government here, though a very traditional one having little if anything to do with resource constraints. More worrisome is the repeat of the oft demonstrated danger that misguided policy actions aimed at addressing the imaginary concern may neglect or even aggravate the real one.

Resource Exhaustion: An Imagined Concern

The first of the quotes presented above came from the Carter White House in 1977. It was intended to be alarming. In much less than a decade, it foresaw energy shortages so grave as to threaten the American way of life. It served as the basis for a wide range of major government policy interventions into energy markets[109], most premised on two assumptions: (a) that the U.S. and the world were in the midst of a worldwide "energy crisis" which was attributable to a massive market failure in the oil markets, and (b) that government regulatory intervention could "remedy" this failure.

---

[109] Including price controls on domestic crude oil and natural gas, direct regulation of fuel use by utilities, establishment of fuel economy standards for transportation, and an array of subsidies to conservation and alternative and synthetic fuels.

Eighteen years later, with the hindsight provided by history, the statement is still alarming, but hardly for either its insight or foresight. Rather, it remains alarming for the scope of the ignorance it exposed, both with respect to the "diagnosis" it offered and with respect to the "remedies" it proposed. In retrospect, there is little disagreement that the policies implemented hinged almost entirely on unfounded assumptions, and by and large aggravated the problems at which they were ostensibly intended to address. But the roots of that ignorance neither originated with the Carter administration nor succumbed to the wholly contrary experience gained in the years since.

The "problem" of resource exhaustion, namely the view that limited natural resources would eventually constrain economic growth, has a long tradition, reaching back at least to the beginnings of the industrial revolution, and extending to the present. Of course, it is a view not limited to petroleum, but much more general in scope.

In 1826, Malthus explained that a rapidly growing population would inevitably collide with a fixed amount of farmland, leading to a world population living perpetually on the edge of starvation. In the early 20th century, the Conservation Movement in the U.S. popularized the notion of imminent resource depletion. In the early 70's, the Club of Rome revived this theme with its alarmist *Limits to Growth* study, which foresaw imminent exhaustion of a number of world resources, including petroleum (which was estimated to be fully exhausted between 1992 and 2003). More recently, the U.N. sponsored World Commission on Environment and Development (the Brundtland Commission) issued a report in 1987 entitled *Our Common Future*, emphasizing a need for "sustainable development" to "meet the needs of the present without compromising the ability of future generations to meet their own needs."

A thread common to all of these pessimistic views of the future has been a static view of world resources, particularly nonrenewable resources, as a pie of fixed size to be allocated "fairly" among generations, and the related views that (a) private markets are not capable of playing such a role, and (b) governments, or international bureaucracies, are better suited to perform such a role. There has often been an urgency expressed in these views that such intervention is needed soon to prevent imminent and irreversible catastrophes[110].

Such views have such strong intuitive appeal as to be often accepted as self evident, or at least rarely questioned. But in the few cases in which they have been questioned, the empirical evidence is striking. Exhaustibility does not imply a necessity, or even a likelihood, of exhaustion. Technology and learning wage a perpetual war against depletion, both via reducing the cost of resource recovery and via the discovery and development of closely priced substitutes. Which force gains the upper hand over the long run is an empirical question.

In one of the most extensive examinations of this empirical issue, Barnett and Morse [1963] examined the long run pattern of prices in a number of key natural resources over a century. They found no evidence of exhaustion of nonrenewable resources. In fact, for most commodities exhibiting any price trend at all, most were downward, and this seemed to be more the case with "nonrenewables" than renewables. Updates of this analysis have consistently reinforced this empirical finding. In 1992, the *World Development Report* issued by the World Bank found that "the evidence ...gives no support to the hypothesis that marketed nonrenewable resources such as metals, minerals and energy are becoming scarcer in an economic sense." Most recently, Adelman [1995] examined a set of commodity prices over time, which also yield no evidence of the sustained increases in real price characteristic of growing scarcity.

Without learning and technical change, depletion would be expected to cause an upward trend in price. However, the empirical evidence shows that, at least to date, and for most resources, particularly those regarded as

110 Brown [1993] writes: "When the history of the late 20th century is written, the 1990's will be seen as a decade of discontinuity -- a time when familiar trends that had seemed likely to go on forever, like smooth straght roads, came to abrupt bends or junctures and began descending abruptly..."

nonrenewable, technology has generally maintained the upper hand.

As was seen in Figure 3, petroleum has not been any exception to this pattern. Not only are resource estimates today larger than ever before, but costs currently are little changed from levels 40 years ago, even in an area as mature as the U.S.[111] Like the hypochondriac whose tombstone read "I told you I was dying," geological assessments of the imminence of oil's demise will someday inevitably prove accurate, as production eventually declines to zero. But there is no indication to date that such a decline is inevitable in the next several decades, or even likely. Moreover, there is also little precedent to suggest that resource exhaustion will be the culprit triggering such a demise. As was described in Chapter 2, the decline in domestic production in the U.S. was not a bellwether of growing worldwide oil scarcity, but actually quite the contrary. That is, it is indicative of the relatively high cost of much of the U.S. oil resource base in the face of an *abundance* of lower cost oil resources abroad, aggravated by increasingly restrictive federal policies on access to the most promising remaining domestic prospects.

Undoubtedly, the ultimate fate of the oil industry will eventually be the loss of market to some competing energy alternative, or to changes in patterns of use which reduce the need for oil. But, based on the information presented above, it would appear unlikely that any such demise will be attributable to resource exhaustion.

From the examples presented in the above chapters, it would appear that conventional world oil resources could support current levels of production comfortably for at least another half century, and perhaps much longer if technical progress continues to offset the effects of resource depletion. Sustaining modest worldwide supply growth at the 1-2% annual rate characteristic of recent years would be more difficult in the absence of sustained worldwide increases in recovery efficiency, but with only modest improvements in recovery world supplies would not necessarily fall significantly below their current levels until well after the first half of the 21st century. Moreover, this does not include the massive volumes of unconventional oil which technology and price could eventually cause to provide multiples of the expected volumes of conventional oil resource.

Most importantly, however, even if recent trends eventually should reverse themselves, to the point that the real price of oil begins to rise for an extended period, there is no reason to expect that market processes would truly exhaust the conventional resource at the point that petroleum production ceased. Rather, the rate of increase in price would be determined by the supply cost of the next available substitute (which, of course, might simply be higher cost oil from Alberta or Venezuela, or simply enhanced recovery of conventional but currently unrecoverable worldwide).

Over the very long term, there is also enormous uncertainty about demand for oil, even apart from deliberate policies to restrain its growth. There is little evidence of any ability to forecast demand trends over such a long period as a half or full century[112]. Experts on oil in the late 19th and early 20th century did poorly on estimating future supply potential (as examined earlier), and as bad or even worse on the demand side. Early estimates of future demand growth were based on its use in the production of kerosene for lighting. At the time, gasoline was simply an annoyingly explosive and otherwise undesirable byproduct of refining crude oil into kerosene for lighting. Its potential significance to future transportation was not appreciated for several decades. Today, as we watch the breakneck speed at which communication technology is advancing into applications increasingly substitutable for transportation[113],

[111] See Porter [1995].

[112] Schelling [1992] presents this view, but it seems to have gained little accepance, as evidenced by the recent "boom market" in the modelling of global climate change and its expected economic and physical impacts. In this arena (see EMF12 and EMF14, for instance), projections a century hence are routinely presented, often without qualification as to the extreme uncertainty surrounding such estimates. In fact, as if such excursions were not enough, one of the more serious critiques of current policy approaches to the potential problem of climate change (Cline[1992]) seriously suggests that models with a horizon of a century or more are *too myopic*.

[113] For example, the fax machine, audio and visual teleconferencing, and electronic mail, have already

some humility about our ability to anticipate demand a century hence would appear warranted.

Such humility would require a recognition that there is no absolute assurance that oil demand will increase over such a long interval as a half century or more, particularly if prices were to substantially increase. On the other hand, should economic growth in areas like Asia continue for decades, there is the possibility that demand could be pushed well above the 1% to 2% growth scenarios examined here.

The experience of 1980 to 1985 showed that at higher oil prices, conservation and supply of conventional oil were far more responsive than had been previously expected. Even a modest secular decline in the growth of petroleum demand could greatly extend the life of the resource beyond the cases considered above, just as a small amount of underestimation could draw down resources far faster than what is suggested here.

Market price signals of increasing or decreasing scarcity are precisely the mechanism via which a market effectively avoids the "discontinuities" problem referred to earlier. In fact, there have been energy transitions before, as England moved from wood to coal, or as the U.S. moved from whale oil to kerosene for lighting in the 19th century, or as the U.S. shifted from coal to oil and gas in this century. In none of these cases did exhaustion occur prior to the transition. In the case of the shift from coal to oil in industrial, commercial and residential use, for example, the shift occurred despite the fact that coal was cheaper and more plentiful than oil. The preference for gasoline over alternatives in automobiles stemmed largely from the advantages derived from the high energy density of gasoline. Private markets in the past have tended to substitute conservation and competing resources far before they exhaust them.

In summary, normal market processes coordinated by price have never exhausted a non-renewable resource, and there is no reason to expect them to do so in the case of oil. At this point, there are no market signals suggesting that world oil resources are yet becoming scarcer than they were a half century ago. In fact, most such signals currently point to growing abundance. Even if at some future point this signal changes, there is no reason to expect that normal market responses would not effectively guide an orderly transition to an alternative fuel, as they have done numerous times in the past[114]. Concerns that government actions are required to ease this transition are simply unfounded.

A Real Problem: Remaining Institutional Barriers

But this does not represent as Pollyana-ish view of future oil markets as it might superficially appear, since there is a second concern that is both more subtle and less easily dismissed. Namely, it is the challenge posed by the growth of world demand, which promises to put a number of strains on new supplies of crude oil worldwide. Even the modest 1% to 2% growth examined in the above scenarios requires development of 7 to 15 million barrels a day of new capacity worldwide within the next decade.

To put this in perspective, today's largest oil producing country, Saudi Arabia, currently produces about 8 million barrels daily. With no major undeveloped discoveries on the horizon, the industry worldwide must develop new capacity roughly equal to one or two times current Saudi output within the span of only ten years. These are large numbers. They require formidable investments. A glance at these magnitudes alone has triggered some trepidation about capital availability. But the magnitude is not the issue, nor is the adequacy of capital investment, provided that a secure institutional framework for the deployment of such capital is in place.

How likely is it, though, that the world can develop such supplies so soon? Certainly, it is not impossible. In fact, it has been done before.

established a rudimentary infrastructure which eliminate or seriously reduce transportation associated with commuting, transporting documents, and travel to meetings.

[114] Of course, this does not imply that such markets are free completely of imperfections such as cartel influences

The first ten million barrels per day of supply took the world about 90 years to develop, but from 1950 to 1980 world production grew by 50 million barrels per day, an average of 12.5 million barrels per day each decade. From 1985 to the present, world supply has been growing at a rate in excess of a million barrels a day each year, implying a growth in the middle of the required range.

In many areas of the world, there is reason for optimism. The collapse of socialism worldwide has encouraged the privatization and liberalization of the petroleum industry in many areas of the world where private investment in petroleum had been seriously constrained or even barred for several decades. Petroleum production capacity from those areas has been growing steadily for three decades, as investment continues to add reserves faster than they are depleted by production. Ironically, however, in most of the largest oil producing countries, there has been stagnation or deterioration in the investment climate.

In the United States, federal constraints on land use have placed many of the most promising domestic exploration targets off limits, and even rendered significant numbers of existing offshore leases undevelopable.

In Mexico, despite significant liberalization of trade and privatization of industry, the petroleum sector remains too highly politicized to allow direct investment in upstream operations.

In Russia, ambiguous property rights and political turmoil add significant political risks to major capital investment. In the newly independent states of the former Soviet Union, investment is threatened by a geography that requires transport facilities crossing a labyrinth of hostile or politically volatile territory.

In the Middle East, the largest producers continue to at least verbally flirt with deliberate supply restriction via OPEC as a solution to short term financial pressures[115]. Apart from such actions, and the tentatively promising prospects for an Israeli/Palestinian peace, there are territorial disputes, new strategic alliances, and a number of imminent succession issues which threaten the prospect of stable supply growth in a key supply region. In virtually all of the scenarios in Chapter 3, and most of those in Chapter 4, there is expected to be a significant increase in the market share of the Gulf region in the next several decades[116], offering significant potential for instability in future oil markets.

In summary, while the required capacity is not precluded by resource availability, it is threatened by a number of serious institutional barriers which discourage investment in all three of the largest producing countries --The US, the FSU, and Saudi Arabia, and a number of smaller but significant producers such as Mexico.

The Role of Markets and Governments

Clearly, exhaustibility does not imply either the imminence or even the inevitability of exhaustion. In fact, there are few if any examples in which an exhaustible resource market actually exhausts the resource. There is a strong theme in the environmental literature that suggests that exhaustibilty itself gives rise to a market failure that requires government intervention. This is not only wrong, but quite backwards. That is, the key characteristic of market failure in natural resource markets is precisely the failure of established property rights that are required for a market to operate efficiently.

Perhaps most ironically, the recent empirical examples of wasteful resource use have been in markets for renewable resources, such as forestry and fisheries, in cases where property rights to the resource are not firmly established[117]. Provided that such rights are

[116] However, the analysis shows that this will last for several decades, insofar as higher cost unconventional oil resources are phased in. Such alternatives are concentrated principally in the Western Hemisphere.

[117] Although in the 19th and early 20th century, the “rule of capture,” which conferred ownership to whoever produced oil from a given reservoir first, led to waste of domestic oil resources by encouraging overproduction by competing producers drawing on the same reservoir. This problem was

clear and enforceable, there is no reason that exhaustibility itself would generate a market failure. In a market setting, increased scarcity signals itself with increased prices, providing incentives to conserve and eroding the competitive advantage of the scarce resource relative to less costly alternatives.

It is quite possible, perhaps even likely, that within a century conventional oil will have become scarce and will have been replaced by a more plentiful alternative. But there is nothing in the past or present to indicate the imminence of such scarcity, and the resource numbers presented above indicate that the substitute may simply be conventional oil produced unconventionally, or unconventional oil, in the form of fuels derived from the Alberta tar sands, heavy oil from Venezuela, or even oil shale from the Western United States.

There may be a role for U.S. policy to reduce or constrain the risk attached to this prospect. For example, government holding of stockpiles, such as the Strategic Petroleum Reserve, is addressed precisely at contingencies associated with temporary loss of supply[118].

More importantly, there is the normal role for government of using diplomatic and military means to secure such trade[119]. Explicitly since the Carter Administration, and implicitly since World War II, access to Middle East oil has been acknowledged to be a central strategic interest of the United States[120]. But it has only been in recent years that the capability to credibly project the force necessary to secure such trade has been developed and refined, as illustrated by the success of Desert Storm in the liberation of Kuwait in 1991, and the 1994 deployment of forces to halt potential new Iraqi incursions into Kuwait.

Nonetheless, there are troubling signs that a lapse of institutional memory could lead to policies which repeat past errors. The approach, occasionally defended as a politically more palatable approach to the security problems associated with growing world dependence on the Middle East, is direct limitation of petroleum consumption or imports via taxes, tariffs, quotas, or a variety of other instruments, or the subsidization of alternative fuels to reduce such dependence[121]. Both approaches have been used at various times in the post-World War II period, and the record is very clear. The government simply never has had sufficient foresight to anticipate the consequences of such limits, nor the ability to prevent the instruments from being “hijacked” in pursuit of unintended objectives. Typically, both such efforts have involved enormous misallocation of resources, and almost without fail have aggravated rather than remedied the problem they set out to correct.

These demand limitation approaches have usually been based on two premises -- that markets fail to anticipate exhaustion, and that the wisdom of government is required to prevent the current generation from squandering resources needed by future generations. Both premises ignore the lessons of history.

Industrial development has several times

eventually addressed via regulatory instruments such as mandatory unitization or maximum rates of production for specific wells, or a number of other provisions..

118 Whether the SPR is the most effective instrument to address this risk, however, is an open question. It is not obvious, for example, that private stocks are not a superior means to address this problem, or that market based trigger mechanisms would not be superior to the current trigger mechanisms. Current mechanisms are highly politicized, and have the potential for aggravating the problem it is designed to address, by stimulating private inventory demand at the time of an SPR release, substantially compromising the effectiveness of the release itself.

119 While this was the direction of U.S. policy since the early 80’s, there has been recent backpedaling on this direction, as the U.S. policy of “dual containment” of Iran and Iraq has involved significant constraints on U.S. company investment activity in both countries.

120 In 1944, Franklin Delano Roosevelt said that “The Middle East is an area in which the United States has a vital interest.” But he also recognized that such a role was not limited to U.S. access, but would be a keystone of world security. He added that “The maintenance of peace in that area ... is of significance to the world as a whole.” This recognition has been consistent to the present. The policy of the Clinton Administration (see Department of Defense [1995]) has recognized that “the importance of Gulf oil to the United States must be understood in its global context. Oil is traded on a worldwide market; a blockage of Gulf supplies or a large increase in prices would immediately resonate through the international market.”

121 The most explicit example of such an approach has been the Energy Policy Act of 1992, which established explicit goals for reduction of petroleum consumption in the United States, particularly in the transportation sector.

undergone major fuel shifts over the past few centuries, such as the substitution of coal for wood, or the substitution of oil for coal. None of these shifts were attributable to exhaustion, nor were they induced or facilitated by government policy. Rather, they have been due to the substitution of a lower cost or otherwise more desirable attribute of the ascendant fuel[122], via normal market processes. In the few cases one can identify of actual or near depletion of a resource, such as whale oil, clearcutting of forests, or overfishing, the problem has generally been associated with the *lack* of well defined property rights in the resource, which precludes the efficient operation of a market in those resources.

In fact, markets do anticipate scarcity and facilitate such transitions. Perceptions of impending scarcity drive prices upward, providing the incentive to cut demand of the shrinking resource and encourage development of alternative sources. Market signals aggregate information from numerous sources in a manner that no government or central planner could ever hope to.

Even when the market process is flawed, as when concentration of supply encourages cartel behavior by sovereign nations, there is reason to expect that the market would discipline that behavior more effectively than unilateral government intervention, which often presumes a wisdom on the part of government that simply does not exist.

It took many years for the U.S. to learn that lesson[123]. From the end of World War II through the 70's, the U.S. repeatedly intervened in domestic and international petroleum markets in usually vain attempts to limit oil imports, usually on grounds that oil was too strategically important a fuel to be left to the capricious whims of the market. Almost without exception, those interventions not only failed to accomplish their stated purpose, but were extremely prone to unintended consequences that usually aggravated the very concerns they had been intended to address. By the late 70's, this was generally appreciated, and the U.S. embarked on a fresh approach, decontrolling U.S. oil markets and exposing the domestic market to world prices. In response to high prices in the early 80's, demand and domestic supply responded vigorously, contributing significantly to the drop in worldwide demand for OPEC oil which led to the ultimate collapse of the cartel's allocation scheme in the mid 80's, and a revival of imports that rewarded key members of the cartel with new demand for their oil. Policy reverted to the traditional role of government -- commitment to security of trade via military and diplomatic actions.

To date, this approach has been largely successful. It has prevented the development of military hegemony over the region by either Iraq or Iran, and has encouraged the development of trade and financial linkages between the West and the Arab Gulf states other than Iraq. Already the policy has weathered three major challenges -- keeping the shipping lanes open during the Iran/Iraq war, driving Iraq out of Kuwait in 1991, and mobilizing rapidly to a renewed troop buildup by Iraq at the Kuwaiti border in 1995. Nonetheless, these arrangements are fragile, and to be successful over the long term will require deepening of trade and financial arrangements far more extensive than currently exist[124].

[122] While oil today is often regarded as "dirty," one of its strongest selling points in the switch from coal was its relative "clean" burning properties.

[123] See, for example, Piccini et al. [1992] for a review of post-WWII energy policies.

[124] In recognition of this, some of the major producers have called for consumer-producer "dialogue" to promote "cooperation" in stabilizing oil markets. Verleger [1993] argues that the cooperation usually proposed involves the establishment of a commodity price stabilization agreement, which would be neither feasible nor desirable. Instead, however, he argues that an appropriate framework for cooperation be that of removing barriers to energy trade and investment, which remain formidable in both the producing and consuming countries. Removal of such barriers, he estimates, could yield worldwide benefits in the range of $80 to $100 billion annually.

Chapter 6.
Summary and Conclusions

> "The optimist proclaims that we live in the best of all possible worlds; and the pessimist fears this is true."
>
> -- James Branch Cabell, 1926

This paper began with the observation that the recent trade press estimates of abundant worldwide oil reserves appeared to be in sharp contrast to a broadening consensus among official forecasts that the beginning of the industry's demise was imminent.

Most recent forecasts by the Department of Energy, the International Energy Agency, and the World Energy Council, as well as numerous private and academic forecasts, predict a peak in worldwide supplies within the first two decades of the next century, even if world demand growth remains in the historically modest range of 1% to 2% per year.

A careful examination of the history and limitations of the geological estimates upon which this consensus is rooted carries a mixed message for the sustainability of future industry supply growth, and for the advisability of alternative government actions to influence these prospects.

The Good News: Resource Abundance

A central message conveyed by the above analysis is one of abundant resource potential. On the basis of proven reserves alone, current world production rates could be sustained for about 45 years. While there are a number of conceptual problems noted with these proven reserve numbers, the central conclusion suggested by those numbers -- that petroleum resources today are more abundant than ever before -- is not seriously compromised by those problems[125].

The periodic world oil resource assessments done by USGS suggest at least the possibility of a similar theme, although appropriately qualified by an acknowledged wide band of uncertainty surrounding such estimates.

However, even this range is too narrow to capture the fully the uncertainty surrounding world supply possibilities. Sustained technical progress in the recovery of conventional oil at rates within the range of U.S. historical experience could support modest worldwide supply growth easily for fifty years, and possibly for another century. Continued progress in the development of unconventional crude sources, such as extra heavy oil in Venezuela and tar sands in Alberta, could greatly enhance such prospects. Even if world supply peaks in the next half century, the subsequent decline is likely to be quite slow, ensuring that oil *could* remain a major source of world energy supply for at least a century.

The Bad News: Opportunities May be Squandered

But the highly conditional nature of these conclusions about resource *potential* should not be overlooked. While worldwide resource abundance offers the world opportunities for sustained supply growth, it must be emphasized that there is no inevitability that the world will choose to exploit such opportunity,

[125] At least at the aggregate level. On an individual country basis, the differences are more serious.

and even less reason to expect it to do so in an orderly manner. There have historically been very wide gaps between potential and realized benefits.

For example, with regard to U.S. and FSU supplies, there are serious institutional barriers to development that could progressively hamper future growth. In the FSU these limits are attributable to political instability; in the U.S., they are attributable to growing federal land access restrictions in precisely the areas most needed to sustain domestic production -- namely the OCS and Alaska. Continued declines in these areas could continue to offset most or all of the unexpectedly high continued growth in other non-OPEC supplies, as they have for the past decade.

Moreover, even in the lowest cost areas of the Persian Gulf, or the prolific areas of Venezuela, there is no certainty that the necessary investment will occur to transform their potential into actual supplies. Even if such investment does occur, there is no assurance that it will be used, or that it might not be intermittently disrupted by Middle East hostilities. The history of the Middle East since the late 70's has been one of periodic sequences of crises, which has more or less continuously kept one or more of the major Gulf producing countries[126] in a condition of restricted supply.

Conclusion: Institutions, not Resources, Are More Likely to Constrain Supply

In summary, there are three conclusions suggested by the above discussion.

First, resource availability is not likely to be a binding constraint on supply growth for at least several decades, quite possibly far longer. Continued supply growth for another half century or even longer is not ruled out by volumes of even conventional oil thought to be remaining in place. Moreover, within the span of several decades, major volumes of unconventional oil resources may become available, much of it in the Western hemisphere.

Second, however, expansion of such supply at even modest growth rates will require substantial investments in new capacity.

Finally, translating resource potential into actual supply may be seriously threatened by institutional barriers in all of the largest current producing countries (the U.S., the FSU, Mexico, Venezuela, and the Persian Gulf), despite the fact that such barriers have been declining in many other areas since the collapse of socialism. It is these institutional barriers that are likely to be more serious impediments to future worldwide oil supply growth than any scarcity imposed by nature.

[126] The Iranian revolution took Iran from the market in 1979, the Iran/Iraq war took both Iran and Iraq out of the market at various times through the mid 80's, The invasion of Kuwait and the ensuing Gulf war took both Iraq and Kuwait out of the market for over a year . Sanctions on Iraq have kept its production minimal since 1990.

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