Clarifying the Limits of Petroleum Production

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Characterizing the Problem

Modern industrial society has been built largely on the abundant availability of cheap energy. Despite cartoons depicting gasoline pumps as one-armed bandits and people taking out home mortgages to pay for a tank of fuel, the reality remains that energy is, as it has been for us, extraordinarily cheap. Gasoline at three dollars per gallon has yet to rival the cost of bottled water. The correlation between prosperity and energy consumption is very strong. This massive energy consumption has been at the heart of economic growth, permitting that growth to seem almost limitless. Indeed there are many authors, even today, claiming that unlimited growth is both possible and desirable. Of course many scientists and engineers contest the plausibility of this and argue that serious attention must be paid to making our activities increasingly sustainable. We need to understand the limits of sustainability for the energy sources on which our society is built. To create this understanding, engineers are challenged to make clear the technical certainties and uncertainties about resource limits.

Sustainability may be an ephemeral goal -- even the universe as we know it has limits. More accurately what we seek is enhanced or improved sustainability. We seek to limit the extent to which current consumption diminishes options for the future. Of course energy is central to considerations of sustainability. From a technical standpoint, there can be no doubt that our current consumption patterns of energy are unsustainable, even in the relatively short-term. Yet, some optimists argue conversely "in the case of petroleum, that point of exhaustion exists somewhere beyond the limits of human imagination."[1] "we now have in our hands -- really in our libraries -- the technology to feed clothe, and supply energy to an ever growing population for the next 7 billion years."[2]

The inability even to imagine the point of exhaustion of petroleum resources evinces little more than an extraordinary lack of imagination. The second quote, from Julian Simon's heavily cited *The Ultimate Resource II,* reflects no lack of imagination, but an appalling lack of numeracy. Had he worked out the math, it would have been quickly apparent that a modest 1% per year growth results in more than $10^{30,000,000}$ people – crammed into a universe comprising some 10^{80} atoms.[3] Indeed our calculations demonstrate that even a total petroleum resource base equal to the volume of the earth would be taxed by growing demand within about 1000 years. Let it be clear there really are limits, the only question is how far can we go before they constrain us? As with many global issues, there is much we cannot know with certainty, but there is much we can know.

Unfortunately the waters of resource analyses have been muddied by justifiable accusations of crying wolf. It is true that some doomsayers have predicted the end of the oil era since its very beginning and they have been repeatedly wrong. However, using the failure of past predictions as a basis for discounting current ones shows not only poor analytical thinking, but inadequate reading of the fable. The little boy was not wrong for crying wolf because the creature he alluded to is nonexistent, but because he did so when the wolf was not yet there. Just so, the fallacies of past prognosticators do not mean that the limits of petroleum production are unreal, but that the analysts erred in their calculations. Some of these errors may merit their own charges of frivolous exaggeration. Indeed some of the current prognosticators appear to make pessimistic assumptions deliberately. The more pessimistic the assumption, the more imminent the crisis, the more shocking are the findings -- and perhaps more newsworthy. Unfortunately, no matter how clear it is that the wolf of resource limits prowls the night, the natural human reaction is to become inured to repeated false alarms of when it will strike.

Misinformation or Poor Sources

Unfortunately, those pointing to what should be the undeniable physical reality of impending petroleum production limits, often exaggerate their cases. By exaggerating, they make predictions that are often surpassed. Once the fallacy of their predictions is clear, it is easy to dismiss the substance as well. A further sad reality is that the public is being informed largely by politicians and journalists. Even a good journalist deludes himself or herself by taking on the role of communicating technical matters. Greg Easterbrook's popular book, *A Moment on the Earth: The Coming Age of Environmental Optimism*, did in fact offer an optimistic view, replete with technical inaccuracies and analytical debacles. He questions the Second Law of Thermodynamics, suggesting that the increasing entropy of the Universe may be a flawed theory, "… for reasons too numerous to mention." When questioning fundamental science, shouldn't one be expected to mention at least one or two of the reasons – or offer citations? In a 698 page book, he offers only 65 end-notes and most of those are additional commentary, not citations of actual technical experts from whom he drew his information.[4]

One of the problems of the non-technical authors serving as the public source of information on technical issues is the failure to question numbers and claims. Howard Geller's *Energy Revolution*, notes the rapid growth in Denmark's wind power industry. He is quite right in describing the impressive growth in wind turbine manufacturing technology that grew from significant government support of the fledgling industry. In fact, the *installed capacity* grew by nearly an order of magnitude in Denmark through the 1990s. This is indeed impressive. However, it should be noted that *installed capacity* does not equal energy production. There is no comment on actual energy production.[5] There should be. The evidence suggests that comparing actual production may show an even larger increase – as the new technologies (e.g. low rpm, high torque) appear to be more reliable than the older ones (high rpm). Nevertheless, *installed capacity* gives an artificial boost to wind power numbers, when comparing to other energy sources, almost always reported in energy production units. Finally, in spite of the impressive growth, it should be noted that the total *installed capacity* for the whole nation was barely that of 2 commercial coal or nuclear plants in 2001. This failure to question and clarify, opens the door to such foolishness from other authors as extrapolating the trend from the dramatic growth indefinitely into the future!

This fallacy is even more clearly made in Figure I, which shows a projection of solar photovoltaic energy production. Through the present date, the curve is too small to appear above the X axis, yet, by the middle of the century it is growing to the point of being able to meet all human needs! (In all fairness, the authors may have acknowledged a problem in their text of the speech from which this graph was posted. Still, it stands on the internet to misinform readers.)

PROJECTED GLOBAL PHOTOVOLTAIC CAPACITY (MW)

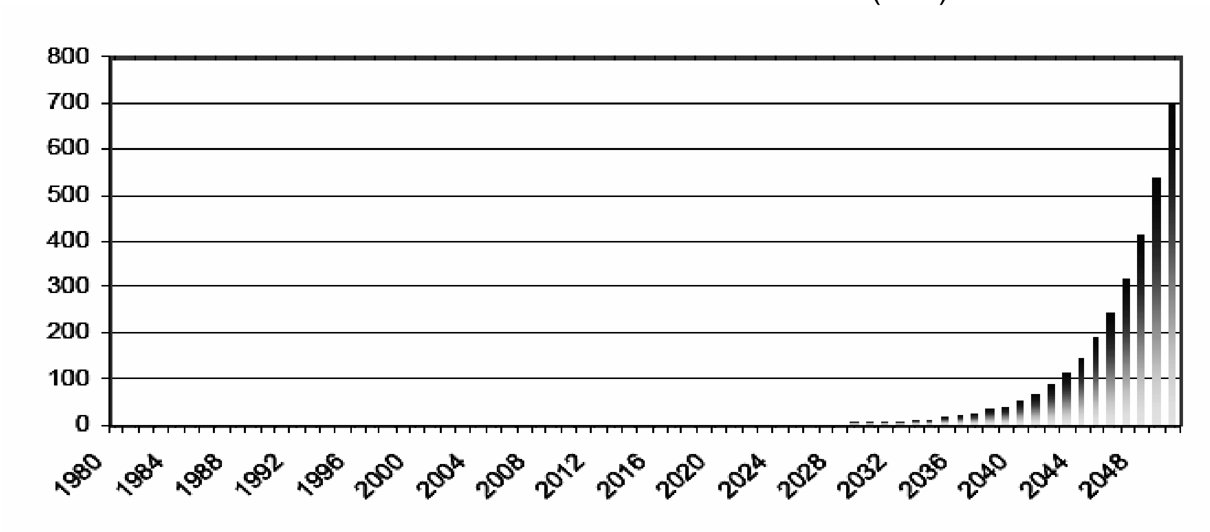

FIGURE I
from World Energy Forum, 5/30/2004 Source: Worldwatch Institute[6]

It is within these muddied waters that thoughtful, engineering-based calculations are called upon to provide some clarity. We may not be able to forecast the precise date on which the real sustained energy crisis will begin, but we can -- with reasonable certainty -- define some limits. Calculations are presented herein that demonstrate an impending shortage by about the year 2035 even with extremely and deliberately optimistic assumptions about the total recoverable petroleum resource base. In the face of repeated failures to predict the onset of petroleum production shortages and the attendant public skepticism, an important first step is to overcome this skepticism with clear analyses of the limits within which petroleum production must operate.

What We Mean by Shortage

The first analytical problem is to clarify what is meant by a petroleum shortage. There is sufficient discussion of 'running out of oil' to generate a pervasive image that petroleum depletion will be seen as a sudden, instantaneous event -- comparable to draining a beverage glass. Therefore the common image held by many people is that one day the world will be producing tens of millions of barrels of oil and the next day nothing. Of course this isn't true. Petroleum production involves isothermal decompression of vast reservoirs, containing petroleum in the tiny pore spaces of sandstone or carbonate rocks. Petroleum must flow through these tortuous pore channels extending across drainage areas of as much as 160 acres for oil. With each barrel of oil extracted, the reservoir pressure declines (under primary production operations without secondary fluid injection), reducing the driving force for subsequent production. Because of the volumes of petroleum reservoirs, the limited permeabilities of the porous rock, and the compressibility of the oil -- and even water -- at reservoir conditions, real fields are often able to operate at or near a *Maximum Efficient Rate* for several years before a production decline is seen. Nevertheless an ongoing, gradual decline in the maximum production capacity of a given field is inevitable. When many fields are aggregated together, the overall production decline is more gradual.

Over the last some 140 years, petroleum demand has been growing approximately exponentially, as shown in the first third of Figure II. A discontinuity can be seen at the time of the 1970s 'oil crises.' In response to the perception of shortage and rising prices, there was an actual dip in global demand. When oil prices fell in the early 1980s, so did the incentive to conserve and the world returned to exponential growth, albeit at a slightly lower rate than the previous trend. With an intractable trend of growing global population, substantial industrialization underway in China and India, and a compelling need for increased access to energy resources for the world's poor, businesses-as-usual dictates an ever growing global demand for the foreseeable future. The petroleum shortage will occur at the point when global production capacity can no longer grow to keep pace with growing demand. As global petroleum production peaks and begins its long, gradual decline, the shortage will be defined by the difference between some hypothetical extrapolation of growing demand and actual production capacities.

This figure has much in common with the curves produced by many authors addressing ‘peak oil.’ A major difference, though, is that the decline portion of the curve is not symmetrical with the growth section. It reflects actual American production decline, which should serve as a better analogy than the simple assumption of Gaussian symmetry.

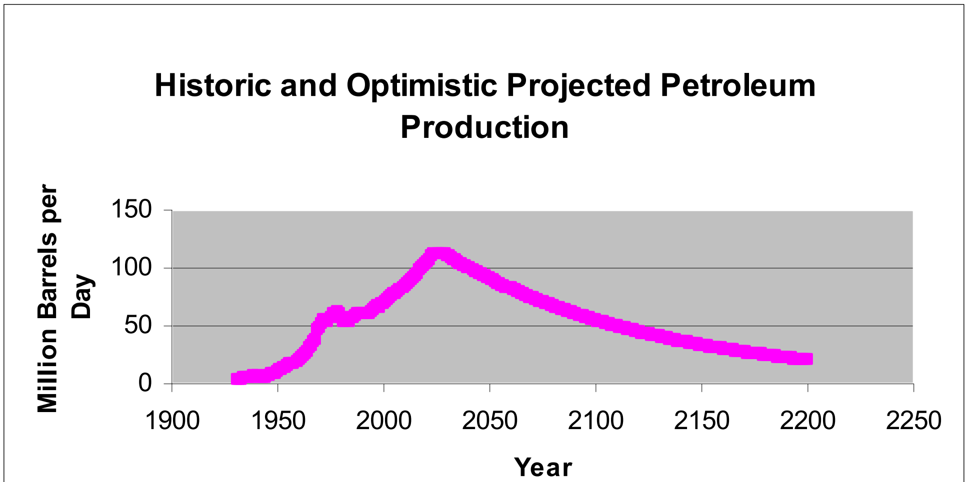

FIGURE II

The Physics of the Limits

It is not surprising that technical experts recognize the reality that petroleum production rates have grown in response to growth in demand and will continue to until they are no longer able to do so. There will be a peak petroleum production, followed by a long decline. In fact much of the current literature is addressing the popular misperception of a sudden shortage with the expression "peak production." What is surprising is that, almost universally, publications by technical experts fail to recognize the controlling phenomena of growth and decline. Production has increased in response to growing demand. Therefore growth has been a market phenomenon. The peak and ultimate decline, though, will be controlled by physical phenomena. The maximum flow rate from any given well or field is a function of reservoir pressures, permeabilities, saturations, and fluid viscosities. Although market forces will promote more aggressive exploration and production technologies, the decline will be governed by the physical limits within which the technologies must be deployed.

Nevertheless virtually every published analysis of global peak petroleum production, assumes that the decline rate will be symmetrical with the growth rate -- defining a nominal Gaussian curve. This assumption is an artifact of the first and still seminal work done to evaluate the future of petroleum production over a half-century ago by M. King Hubbert. When King Hubbert did his work, absent any significant regional decline data, it made sense to employ the simplifying assumption of symmetry. In the early 21st-century, though, there is no reason to cling to this artifact. Total crude oil production has been in decline in the United States for some 30 years, providing a better analog for global production decline behavior than assuming symmetry. US production decline has averaged about 1% per year. This is not much lower than the 1 1/2 to 2% per year demand growth patterns, but still proves very significant in terms of the amount of oil expected to be produced after the decline begins. Unfortunately, most of the current authors base their entire work on the flawed assumption of symmetry. Vaclav Smil observes, "… violating the symmetry of the Hubbertian exhaustion curve, and thus undermining the validity of the key forescasting tool used by the proponents of an early-end-of-oil era."[7] This is an unfortunate fallacy, as it fits with 'chicken little' dire predictions that are subject to a great deal of criticism, drawing attention from the core reality of resource depletion.

Therefore, it is likely that the decline will be much shallower than the growth side of the curve, meaning that more oil may be produced under decline than in growth. This observation is significant in addressing some of the optimistic pronouncements about Enhanced Oil Recovery, commercialization of currently marginal fields, and exploitation of unconventional petroleum sources. The vast majority of petroleum shortage estimates start with some guess as to the world's ultimate, recoverable petroleum reserves. Those predicting impending shortage commonly take relatively conservative estimates of the ultimate global reserves, commonly in the neighborhood of 2 trillion barrels. They thus opened themselves to criticism from the optimists, who argue that they did not pay adequate tribute to all of the potential reserve additions from application of improved technologies in the categories named above. Some of these criticisms are legitimate. Some of the pessimists go so far as to claim that enhanced recovery technologies do not actually enhance recovery. Their claims are flawed by comparing infill drilling with enhanced recovery and drawing conclusions about enhanced recovery technologies based on demonstrable market changes rather than technical factors.

In fact the optimists are probably right that the world will yield far more oil than the pessimists claim. Consider not only the technologies of enhanced recovery and the like, but limited exploration in large sections of the world. The sedimentary geologic basins of Africa's interior are an order of magnitude larger than the basins of the US, with two orders of magnitude fewer wells drilled. Much the same can be said for South America and portions of Central Asia. Further complicating the issue is the fact that there is an enormous disparity between commercial thresholds in international versus domestic exploration. This is to say that the relatively small number of wells drilled in Central Africa and South America have identified substantial oil and gas resources that were never developed or booked because they were well below the economic thresholds of the international export market. This represents a potentially large window of opportunity for local development in the lower income countries. It will no doubt add noticeably to the world's ultimate reserves. [These long unexploited resources in Lower Income Countries actually afford the basis for a development project, the nonprofit AHEAD Energy Corporation, based on the University of Rochester campus. AHEAD seeks to identify bypassed resources (particularly natural gas) as a first transition away from unsustainable fuelwood dependence in many regions. In addition, it seeks to integrate such natural gas development with non-depleting alternative energy sources, so as to plan for a deliberate and smooth transition from depleting fossil fuels to more sustainable energy sources. This effort points clearly to how much oil and gas lies untapped in Lower Income Countries. It also highlights the need for energy resources to be developed in those countries, suggesting a likelihood that they will contribute to the global resource base, but perhaps not help soften the blow for gluttonous western consumers. In America, where 5% of the world's population consumes 25% of its oil production, we need to find ways to consume less.] Many oil and gas resources have already been identified by international exploration, but lie untapped due to the economics of international markets and lack of incentive to develop them for the modest local markets in the poorer countries.

Some portions of the larger potentials discovered will no doubt enter into the international oil and gas trade as prices rise.

Potential for future discoveries figure largely in the low ultimate, recoverable reserves numbers cited by many. Dr. Colin Campbell, a retired exploration geologist, has been one of the most quoted and vociferous prophets of the coming shortage. His observations are based on the solid geologic reality that oil and gas resources have practical limits. The global production capacity will no doubt be exceeded by growing demand in a relatively short time. He brings practical understanding of the geology to the debates. Unfortunately, he is less versed in operational aspects and makes a few mistakes that may jeopardize recognition of the important points he makes. As previously mentioned, there is no physical reason to expect symmetry in the growth and decline portions of the global production curve. He does view the problem from different angles, but misses some operational points there as well. For instance, in Figure III, he shows the global discovery rate: an important aspect of future production capacity. However, he seems erroneously to extrapolate the latest established trend of declining discoveries, in spite of the clear evidence that discoveries peak and decline with price. Discoveries were clearly in decline several times in the past, but price increases also drove discoveries up. In fact, his extrapolation represents a discontinuity with the actual data. The last real data show discoveries rebounding after the price spikes of the 1992 Persian Gulf War. Nevertheless, he begins an unmitigated decline in discoveries in the midst of that rebound. Much of the world has little exploration and even less production. There will be additional discovery peaks in the future.

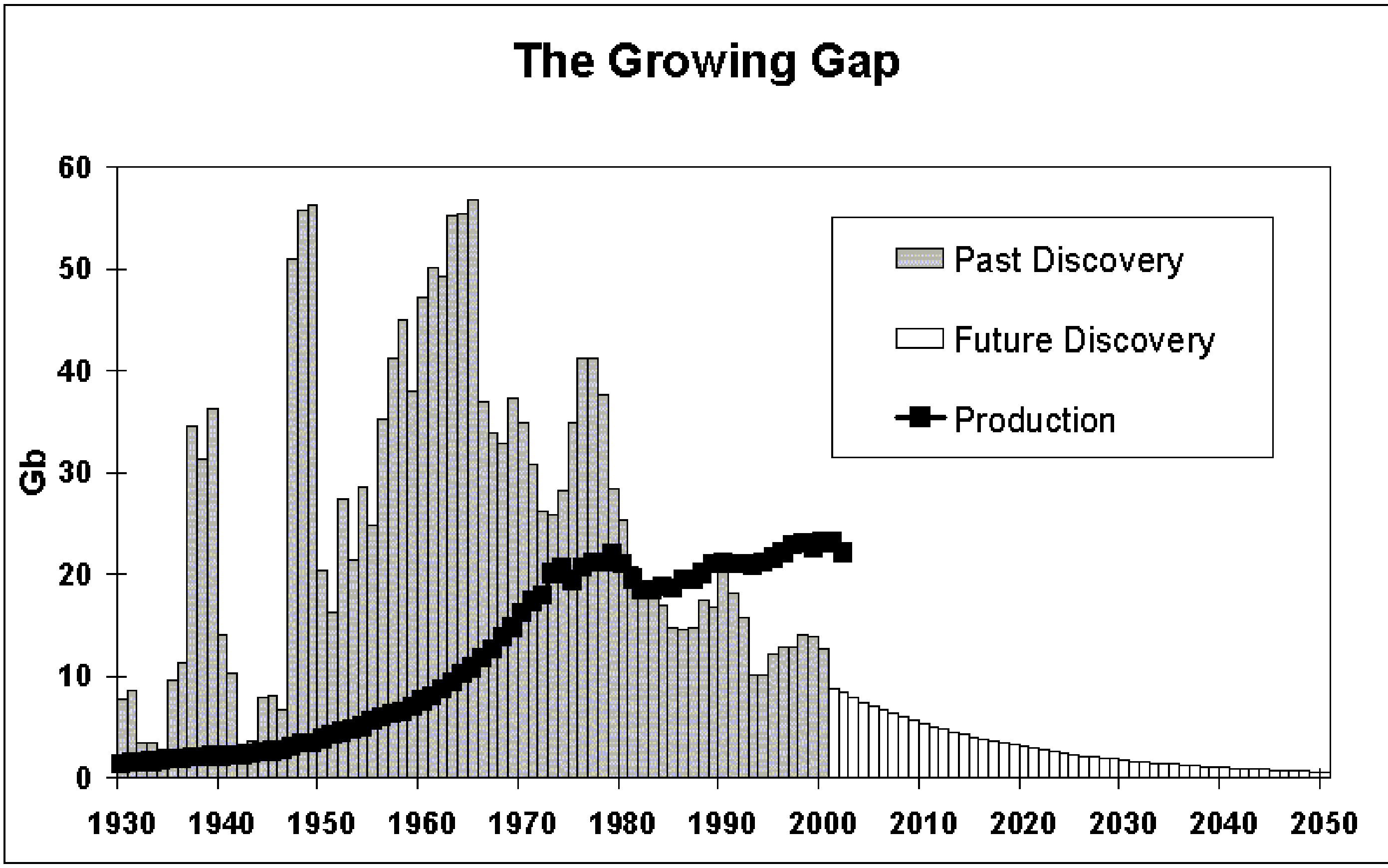

FIGURE III
From: Colin Campbell, ”The Coming Global Oil Crisis[8]

The problem of relying too heavily on the expertise of one technical specialty is also seen in the faulty conclusions drawn regarding Enhanced Oil Recovery (EOR). In an otherwise very informative article, Messrs. Zittel and Schindler says the following about EOR:

> EOR measures have already been applied for more than twenty years, and these measures are accounted for in production forecasts. There will not be any sudden jump in the future – continuous progress is and was always part of the production forecasts. There are two major examples for this: (1) One is the production profile of German oil. After its peak in 1968 the production continuously declined despite efforts to implement enhanced oil recovery techniques. (2) Another example is the production of Prudhoe Bay as already explained in figure 3. This field is at the technological forefront and every possible new measure was exploited to enhance production and to avoid a decline, with almost no success. Today more water is extracted from the wells than oil, water which was injected into the field to increase the pressure.

- EOR measures are only applicable beyond peak production when the pressure level is low. These measures cannot revert a decline into an upward production profile for any substantial period of time.

- EOR measures are most effective in certain fields with complex geology which exhibit a low recovery factor.

- These measures are only effective in the sense that more dollars are gained with the extra oil than have to be spent for the measure.

- Usually these measures increase the production rate for a short period of time, but enhance the decline in the long term – [9]

They are right that EOR is not a panacea for petroleum production declines, but mistaken on several operational points. First, the measures are best applied before decline begins. This is especially true for petroleum reservoirs at initial pressures above the bubble point. Pressure maintenance can then prevent gas dissolution, forming a third phase in the pore channels. (Water is ever-present, thus oil, water and gas would constitute a 3-phase fluid flow regime in tortuous, capillary pore channels.) Furthermore, since gas mobility is much greater than oil's, it will tend readily to channel to the well-bores, 'gassing out' the producing wells. This was not well recognized for many years, thus older fields on any form of EOR (including simple water-flooding), may offer very poor examples of EOR potential. EOR measures are widely varied in characteristics. While it is true that thermal recovery is most applicable to reservoirs with low primary recovery factors (due to fluid, not rock properties). The benefits of steam injection (or more dubious fire flooding) are almost exclusively related to very heavy, viscous oils, which may not flow at all under ambient conditions. However, for some of the more promising miscible injection projects, reservoir homogeneity is a greatly preferred condition. Finally, the successful application of EOR should yield additional oil, not simply offer a short-term production increase, followed by a steeper decline. The net oil production decline may be steeper, due to 'flush production' being chased by injected fluids. The trends of field production that many authors are misled by is also a function of price. A great many fields that were subjected to exotic EOR techniques in the 1970s were beginning to experience production increases by 1980. Prices fell shortly thereafter and field investments dropped with them. Thus, we would suggest that the skepticism about EOR is based, at least in part, on a failure to account for decreased investments in the 1980s. EOR will, no doubt play and has no doubt played a significant role in moderating the decline rates of many large fields, which will, in turn, moderate regional and global decline rates. The world is almost certain to produce more oil than the 1.8 trillion barrels being cited by Campbell and others, but more than half of that will likely come after the decline begins.

In order to refocus the discussion of oil conservation, the following points have been submitted. First, the problem of oil depletion does not refer to the end of useable oil, but instead it refers to the point in time that oil changes from abundance to scarcity. Second, peak oil has always been assumed to occur when oil reserves were half empty. We believe that the peak will instead occur earlier due to a shallower decline than many expect. A third important point is that this problem is not totally uncontrollable. By conserving our resources and increasing engine efficiencies we may be able to extend the exact date of peak oil by over a decade.

The key to oil prices is not how much we have, but how fast we can extract it. Even if demand were to triple next year, prices would not increase significantly if oil production could easily keep pace. Of course, it is highly unlikely that petroleum production could triple, but how much can it grow? The problem arises when demand overtakes the rate at which oil can be produced and refined. This produces a seller's market. The price of oil is bound to rise. This would indicate that one of the most overlooked numbers is that of surplus capacity. This property specifies how much more oil can be extracted at a given time. As surplus capacity reaches zero, the consumers will be at the mercy of the producers. Numbers suggest that this event will occur within the next decade. While it is true that surplus capacity is added every time a new field goes online, most of the high capacity fields have already been or are currently being exhausted and recent evidence shows that new discoveries are currently few. While, as mentioned above, there will probably be increases in discoveries, they will probably only occur when increased prices drive more aggressive exploration. This will probably occur after the surplus capacity has disappeared. The end of surplus capacity, not necessarily peak production will mark the beginning of the energy crisis.

Since Dr. Hubbert accurately predicted US peak production, many have accepted the idea of production following a Gaussian curve. However, it may be more accurate to view a curve that peaks before reserves are half exhausted. The incline of production is governed by demand. On the other hand, the decline will be controlled not by market forces but by physical limitations. The world's thirst for oil allowed for a steep incline to the curve. Simulations suggest that the decline may be significantly shallower. This is due in part to future improvement in techniques of enhanced oil recovery. There are also many smaller, less cost effective sites that have yet to be exploited. As prices rise (and they will), companies will begin to develop these new reserves, essentially dragging out the tail end of the production curve. If this is the case, then most of the current predictions of peak oil which are based on reserves will prove to be several years too late - or they will grossly underestimate the total amount of oil ultimately recoverable. Ironically, those prognosticators relying on a symmetrical Gaussian curve, could be pessimistic about the total recoverable oil, while erring optimistically about the timing of the decline.

Using the data provided by the Energy Economist, one could estimate the number of years before OPEC surplus capacity is exhausted.[10] Assuming a modest 1% growth every year, the reported OPEC surplus capacity runs out in the year 2008. According to the Independent Petroleum Association of America, OPEC possesses 85% of global surplus capacity.[11] This adds one more year until exhaustion. Therefore, by 2009 the global oil production will have leveled off if it has not already begun to decrease. Using data provided by CERA confirms that surplus capacity should reach zero by 2010. These calculations do not take into account any new discoveries. However, significant discoveries have been sparse since the early 1980s. Even with more aggressive exploration by the oil companies, today's surplus capacity would be emptied by the time any new discoveries went online. Furthermore, with as many aged fields as we rely on today, we will need new discoveries just to make up for the lost production due to each individual field's decline. These calculations would make it seem likely that the end of this decade will see soaring gasoline prices and prove to be the beginning of the long anticipated oil crunch. Of course, estimates of global surplus production capacity are highly speculative.

A report by the Center for Strategic and International Studies claims that Saudi Arabia alone can be expected to produce 22.5 million bpd by 2025.[12] This more than doubles the current production rate of 11 million bpd. It is obvious that these numbers conflict with those reported by the Energy Economist. However one must wonder how this production rate is to be achieved. Considering the magnitude of this increase and the fact that all of their oil already comes from a handful of giant fields, one could dismiss the idea of a new discovery accounting for this. High expectations may be based on Enhanced Oil Recovery, leading to greatly increased reserves. EOR techniques extend field life and ultimate recovery, but are not likely to provide any sudden increases in production. Realistically, the sudden production increase could only come from a large surplus production capacity unaccounted for by the Energy Economist study. Who is right? Since much of the data that lead to evaluating production capacities are proprietary, only the future will show whether the surplus capacity is nearing zero, or can support another 30 years of growth in demand. We can't know at this time. This problem can be likened to a person drinking through a straw. One would never know the drink is almost empty until they find that no more liquid is coming out.

The critical point is that when surplus production capacity reaches zero, further growth in petroleum production will be constrained. Production will probably continue to grow somewhat, but not at its previous pace. This will be the beginning of the shortage – even before peak oil is reached perhaps.

Limits

So, it is clear that production capacity relative to demand will be the factor involved in the shortage. As global demand continues to grow, total production capacity is likely still to be growing when the shortage occurs. It will simply be overtaken by the greater growth in demand, as surplus capacity (the difference between total capacity and demand) goes to zero. This is an extremely important factor in understanding the coming energy transitions. It seriously calls into question the potential of some alternatives to play a significant role in mitigating the shortage. When the problem is miscast as “running out of oil" it is possible to see any alternative as playing a significant role, merely by having a significant resource base. It is clear, though, that the alternatives must have large production capacities.

Oil shale is an excellent example of this problem. Its global resource base is unquestionably large, probably at least two to three times the size of the global ultimate petroleum reserves. Of course comparing *resource bases* to *reserves* invokes a substantial misrepresentation. *Resource base* refers to the total amount that exists, while *reserves* normally refers to the amount known to exist and believed recoverable. With ultimate recoveries from any given oilfield only in the range of 30% of original oil in place -- and many "oil shows" never being produced at all -- it is clear that the global petroleum resource base is several times higher than the ultimate recoverable reserves. Even ignoring this problem though, oil shale has no technical potential to match the productivity of petroleum. It does not flow from the reservoirs. It is typically mined, crushed and retorted. Consider that commercial scale ventures, such as Unocal's Parachute Creek project in western Colorado, target production rates on the order of 10,000 barrels of synthetic crude oil per day. It would take nearly 2000 such projects, extracting some 20 million tons of rock per day, to meet American petroleum demand. So far not one has been commercially successful.

Whereas the Parachute Creek project involved a drift mine into the side of a mountain, much of the touted oil shale production potential would come from strip mines. Based on relatively high oil shale yields exceeding 30 gal. per ton, such as realized at Parachute Creek, it still requires more than a ton of oil shale rock per 42 gal. barrel of oil produced. With American oil consumption currently at 18 million barrels per day, it would require more than twenty million tons of oil shale extracted per day. This would constitute an order of magnitude increase in total strip mining in the United States over the current roughly three million tons of coal strip mined per year. Certainly the environmental sustainability of such an activity is highly problematic.

Nevertheless, the US Naval Petroleum Reserve has recently issued reports on the Strategic Significance of America’s Oil Shale Resource. They speak of reaching a possible target production level of 2 million barrels (requiring at least 2.5 millions tons of rock retorted) per day by the year 2020. This still does not account for the extremely energy intensive nature of the overall oil shale process. Nor does it account for increasing energy demand. The government is estimating US liquid fuel consumption to exceed 26 million barrels per day by that time, making that aggressive goal amount to no more than 7% of projected American demand. Still, the government report cites oil shale as able to meet America’s needs for 100 years.[13] This appears wildly optimistic.

Furthermore, the environmental impact of such large-scale extraction must not be ignored. The residue from surface retorting occupies more volume than the original rock. Waste disposal is a very large issue. The crushing also produces ultra-fine particulate matter, which calls for vast quantities of water to keep the particulates from becoming airborne. The only plausible hope to avoid the environmental impacts of oil shale would be *in situ* retorting – a technology sufficiently promising to keep Royal Dutch Shell interested in it, but still probably very energy intensive.

The Outcomes

The world can clearly expect a shortage of petroleum within the next one to three decades. The price changes seen in 2004-2005 are almost certainly reflections of temporary shortages – and perhaps perceptions of shortages – related to international political events, including the war in the Mideast. The real shortage has yet to arrive, but it will soon and its effects can be expected to be much larger. The politically-induced market disturbances of the 1970s suggest an example, however. As Figure IV demonstrates, the real, time-discounted, price of petroleum nominally quadrupled over the 7 year era.[14]

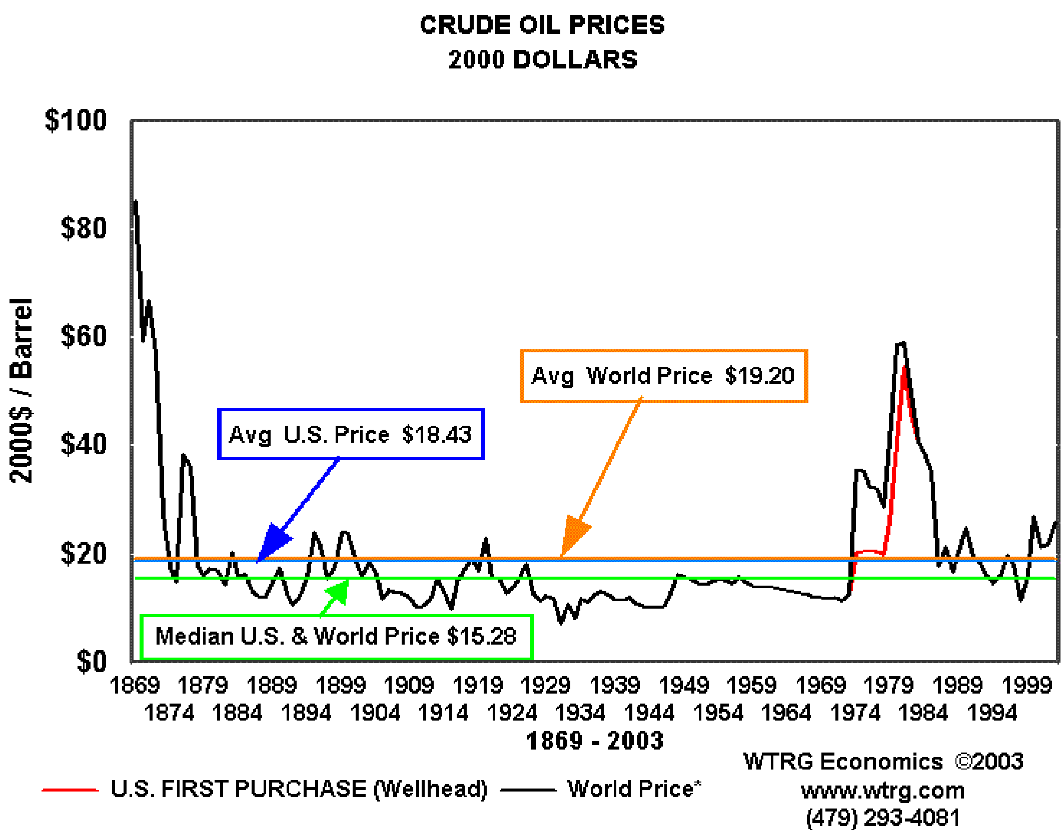

FIGURE IV

Gasoline prices followed suit. There is every reason to believe that the response to a real shortage will be at least as large as, if not larger than, the response to the relatively short-term disruptions of the 1970s. The world is likely to face at least the equivalent of $120/barrel oil at the time of the transition (in today's dollars.) This will correlate to gasoline prices in excess of $6/gallon. If the shortage prevails for more than a few years, the prices will likely rise much higher. It is important to bear in mind the minimal actual role that energy prices currently play in the typical consumer's finances. The average American spends only about 5% of his or her income to consume energy at twice the per capita rate of most of the affluent world and perhaps 80 times the rate of the world's poor (who in turn may spend a third of their household income for their meager consumption.)

There is good news for those in the US. Energy consumption is extraordinarily high and relatively wasteful. Because our driving habits are so wasteful, there are many ways of improving energy efficiency. In a simulation, we tested the effects of 1% of the US fleet increasing their fuel efficiency by 50% every year. This is not unreasonable. One could easily imagine an SUV owner getting eighteen miles to the gallon trading for a smaller vehicle which gets twenty-seven. This improvement could also be assisted by increased use of mass transit, decreased rates of acceleration and cruising speed, and better planning to reduce time spent in the car. The results of the simulation reveal that this modest change could not only overcome the increased demand brought about by a growing population but even save over 12,600 million barrels of oil over fifteen years.

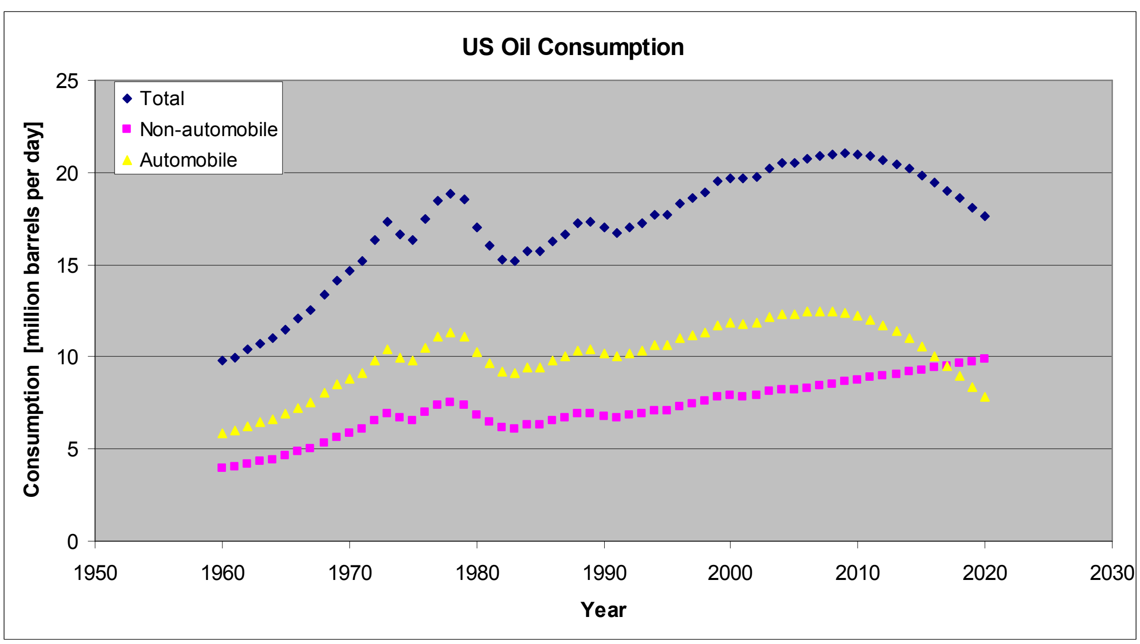

FIGURE V

Of course, if these transitions begin after the petroleum limits are seen, the effect will be marginal. Global consumption has been growing at more than 1.5%/year. Soon petroleum production will no longer be able to support that growth. We cannot predict precisely how the shortage will unfold. Since the first real shortage occurs at the inflection point, when the maximum *rate of growth of petroleum production* decreases, there will be some period of modest impact. How sharply the transition from growth to decline occurs will be critical to the impact on society. If the turnover from inflection point to full-scale decline were to take a decade, market forces might actually be able to respond adequately. Considering the numbers, though, this seems extraordinarily unlikely. In order for the transition to be that smooth and not yet to be underway, either the global decline rate must be significantly higher than estimated herein or the global recoverable resource base must be greater. Since the entire analysis is predicated on taking optimistic extremes of recoverable oil, the latter can be practically ruled out. The decline rate shown in these analyses is shallower than in most published works, as it was based it on a real decline analogy to that established for the US, rather than on the numerically simple assumption of symmetry. The shallower decline rate is optimistic in terms of impact, but pessimistic in terms of timing. If the decline were much steeper, the transition from growth to decline could occur later or more gradually. We believe, though, that the analogy to observed decline for the United States is a much more robust analytical choice than symmetry. There is considerable reason to expect that the effects of Enhanced Oil Recovery, unconventional oil, and remote exploration will all contribute, but slowly.

There are also developments in alternative energy, e.g Iceland's bold plans to use wind and geothermal capacity to become the world's first major hydrogen exporting country (HPEC?). What is clear from the preceding analyses, though, is that the timeline is harsh. New technologies will require time to mature and take up any significant market share. Once the 'fat' of unnecessary consumption is trimmed from the system, only significant market penetration of alternative energy technologies will stop ever-increasing energy prices. The time frame is very short for the development and deployment of new technologies. The time can be extended with substantial conservation efforts undertaken promptly. However, the alternative technologies will need to be pursued aggressively, yet thoughtfully. Some of the technologies promoted by policy analysts have little potential to contribute positively in the transition towards more sustainable energy sources.

As engineers, we must provide clear and compelling information to the public and to policy makers, to support prudent decision-making. The next analytical step is to assess the potential of various energy alternatives in contributing to the transition.

Endnotes

[1] Tippee, Bob, *Where's the Shortage?,* PennWell Publishers, Tulsa, OK 104 (1993)

[2] Simon, Julian, *The Ultimate Resource II,* Princeton University Press, Princeton, NJ 410 (1996)

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