Title: Hubbert Was Wrong: A Tale of Two Sigmoids

Date: 28 Mar 2017

Synopsis: An energy analyst's explanation of the lessons and limitations of peak oil analysis, as well as a prediction of future global consumption

Tags: oil, peak oil, Hubbert

HUBBERT WAS WRONG:
A TALE OF TWO SIGMOIDS

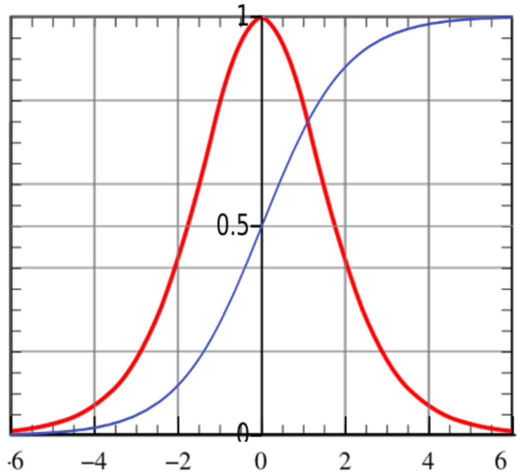

Figure 1 – Symmetric Sigmoid (red) v. Classic Sigmoid (blue)

Contrary to widespread misunderstanding, Dr. Marion King Hubbert did not fit a generic or Gaussian bell curve to his data plot of oil production numbers. Rather, his eponymous curve is a specific mathematical construct that emerges from his mathematical assumptions. I will show below why I believe that those assumptions and the curve are both wrong, and suggest a substitute curve and worldview for crude oil production. The real power of a theory is its predictive power. Based on my modeling and analysis, I predicted in 2012 the exact level of U.S. oil production at which prices and production would collapse in 2014. The same methodology leads me to predict that U.S. crude oil production will perpetually seek a natural level of 9.5 Mbpd (mmbpd), and that global oil production/demand will continue to grow to eventually plateau at approximately 160 Mbpd.

The Math of the Hubbert Curve

There are dozens of different mathematical functions that yield bell-shaped curves. The "Hubbert" or "Peak Oil" curve is actually a special case of a class of s-shaped curves called *sigmoids*. While most sigmoid functions begin and end at different values, Hubbert's curve is constrained to begin and end at zero by the formula and boundary conditions imposed that represent a perfect mathematical translation of Hubbert's worldview. The curve reflects a battle between two competing forces or trends – one for growth and one for contraction – where the balance shifts between the two along the way.

The curve is usually plotted as the annual quantity of oil produced on the vertical scale against the year of production on the horizontal scale. However, the math of the curve is best understood as a differential equation relationship between the rate of oil production (***dQ/dt***) and the cumulative quantity of oil so far produced (***Q***). This is because Hubbert derived the curve by assuming the forces that affect oil production were related to ***Q***, not a function of the year of production. There are three variables that are adjustable to shape the curve: first is Q_0 that starts the curve and is usually set to be zero in the year 1859 when the first commercial oil was produced in the USA; second is a rate scalar ***r*** that symmetrically adjusts the steepness of the rising and falling slopes; third is Q_{max} – the postulated maximum amount of oil which can ever be produced from the geographic area under consideration, and which corresponds to the area under the curve. By adjusting ***r*** and Q_{max}, Hubbert and his acolytes have been able to get a good fit to historical U.S. oil production through about 1990 with some significant caveats. Hubbert's 1956 predicted production curve for USA based on his estimate of total recoverable reserves of 200 billion barrels is shown below. It is followed by a plot of his curve overlaid with actual historical production through 2015.

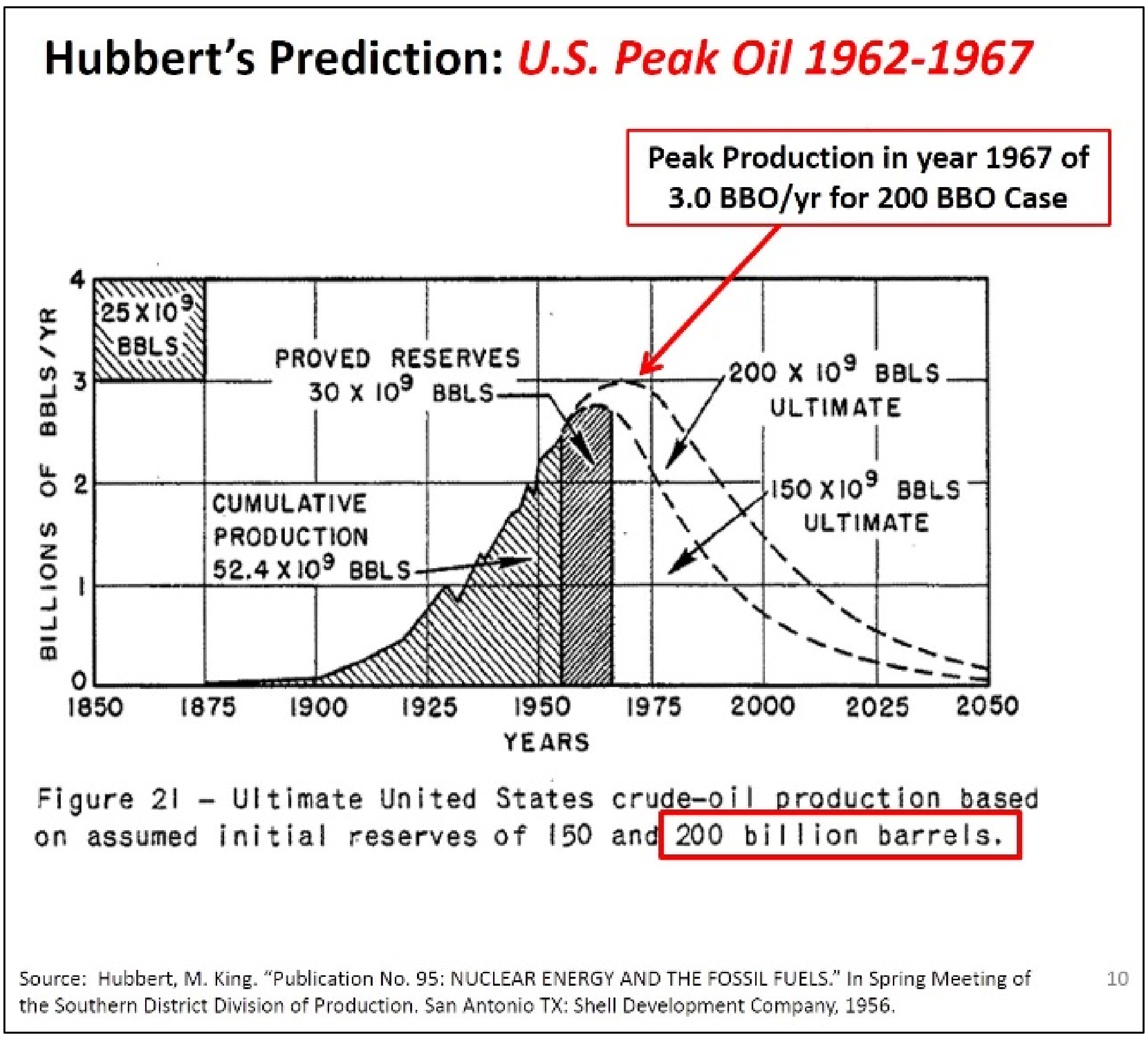

Figure 2 – Excerpt from Hubbert's 1956 Paper (annotated)

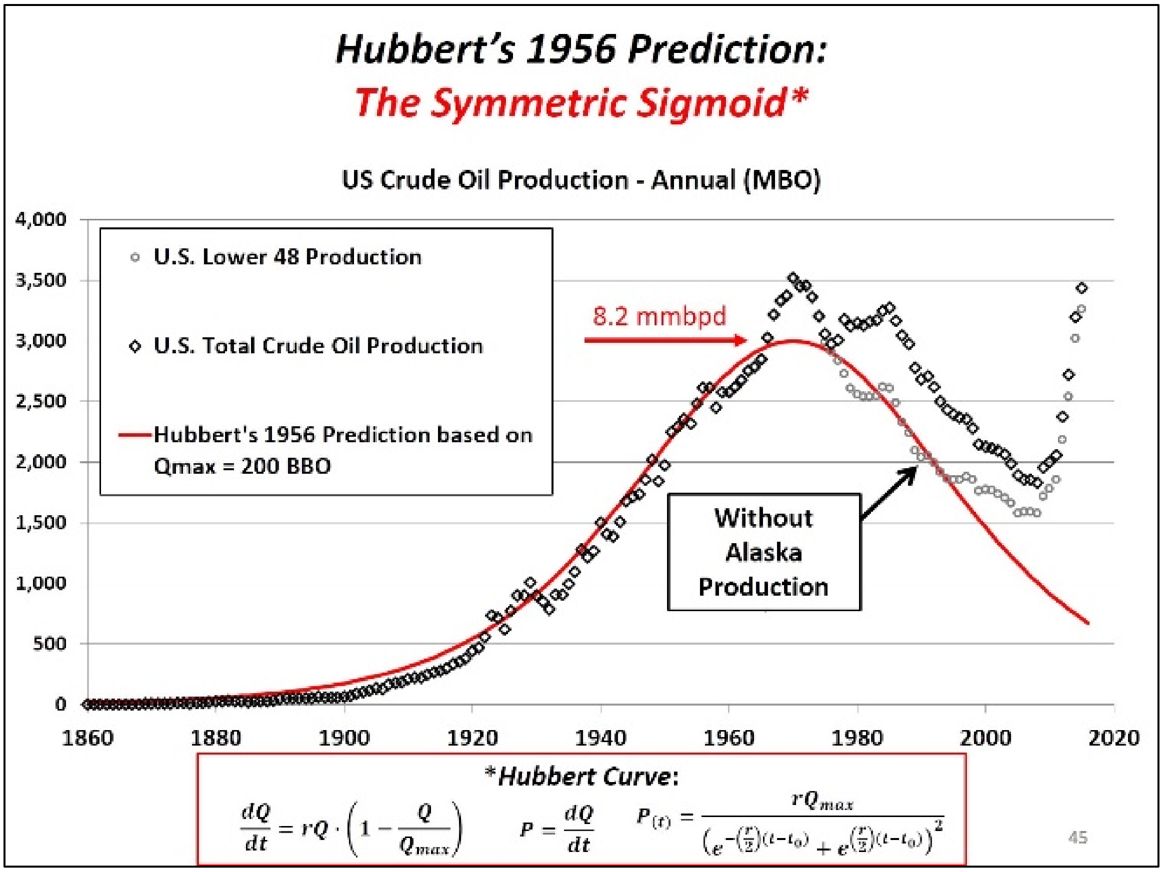

Figure 3 – Hubbert's Curve v. Historical U.S. Crude Oil Production

The formula for the rate of production ***dQ/dt*** shows the two trends that are competing with each other. First there is a term ***rQ*** that tries to increase production in linear proportion to how much oil has already been produced. This term essentially models a scenario where more oil production stimulates proportionally increased consumption, driving more producers to enter the oil business and drill more wells. Unchecked, this portion of the formula would cause the curve to grow exponentially. However, the check comes in the second term, $1- Q/Q_{max}$, that applies brakes on the rate of production in proportion to how close ***Q*** approaches a pre-determined maximum value. The second term essentially models a scenario where there is a fixed amount of a resource in the ground and it becomes harder to find and extract as the balance remaining decreases. Q_{max} is the key assumption and guiding worldview of Hubbert's approach and curve. The two terms work together to produce a symmetric sigmoid, where unconstrained growth dominates initially, but is eventually overtaken by insurmountable resistance, and production reaches zero as ***Q*** reaches Q_{max}. Hubbert's curve is an elegantly simple model of more and more people looking for a scarcer and scarcer resource.

Limitations and Hidden Assumptions of Hubbert's Worldview:

The Hubbert curve is appealing because of its simple logic and because of its close apparent fit with the data through the U.S. production peak in 1970. But is the math too simplistic? Indeed, there are three principal weaknesses that flow from questionable assumptions. First of these is that Hubbert simplistically focused only on production, with no separate consideration for the demand side of the economic equation. Whatever is produced is assumed to be readily consumed and thereby to maintain a constant economic pressure favoring increased production (i.e., keeping the rate coefficient ***r*** positive and stable). Secondly, he assumed that scarcity alone limits production, as discussed above. Thirdly, his approach has baked into it the assumption that the rules are largely fixed for the entire lifespan of production – particularly the rule that oil is monotonically more difficult to extract with every barrel. To be fair, Hubbert did allow for some minor growth in reserves over time due to continued exploration and improving technology, and this is seen in the fattened post-peak tail of his curves as plotted in his 1956 paper. But he did not allow for the possibility that technological progress and evolving geophysical understanding might be great enough to actually reverse the overall trend of slowing production that was supposed to be inexorable beginning with the 1952 inflection point he saw in U.S. production data and built into the Hubbert Curve.

In the case of U.S. oil production, Hubbert also made a fourth mistake – he assumed a self-contained economy where U.S. production was firewalled to satisfy U.S. consumption. The truth is that oil was already well-established as a global commodity by 1956, and it has only become more so with time. Today there are more than 80 countries offering crude oil for sale on the global market. U.S. refineries were never obligated to buy only domestic crude, but rather shopped the international market for best price. In the real world where oil-producing nations compete, oil production is a function of market share (the demand side of the equation intrudes again). And, since the bulk of U.S. oil company exploration and production investment from WWII forward was overseas, it is only natural that the fruit of that investment would be overseas. The "lower 48" U.S. production data that Hubbert was trying to fit with his curve does not include imported oil resulting from U.S. capital investment in Saudi Arabia and Nigeria and many other locations that arguably produced U.S. oil, regardless of nation of origin or subsequent nationalization of assets.

History has invalidated each of Hubbert's assumptions. A host of technological and scientific innovations has dramatically recalibrated reserves, costs, and efficiencies for both terrestrial and offshore oil. Whole new realms of reserves have become accessible and economic, including terrestrial source rock and offshore "pre-salt" oil, upending long-held geologic assumptions. As oil production has continued beyond the 1970 U.S. peak, neither the U.S. curve nor the global curve has cooperated in following the mathematical predictions. Instead, U.S. production has waxed and waned and waxed again dramatically reflecting how, like all commodities, oil production remains responsive to factors which have always affected competitiveness and market share such as government policy and regulation, capital investment cycles, and economic boom and bust cycles.

Hubbert's initial prediction in 1956 was that U.S. oil production would peak between 1962 and 1967 at no more than 3 billion barrels per year (8.2 Mbpd) based on 200 billion barrels of ultimately-recoverable oil. His global prediction was for production to peak in 2000 at 12.5 billion barrels per year (34.2 Mbpd) based on 1.25 trillion barrels of ultimately recoverable oil. Instead the USA has now twice peaked at 3.5 billion barrels per year (9.5 Mbpd). Global production has already exceeded Hubbert's estimate of ultimately recoverable oil, and global proved reserves have been growing faster than production on a secular basis since 1980. Global crude oil production is already 150% of his predicted peak production rate and still climbing. However, those who have convinced themselves of the Peak Oil thesis see the world ever on the edge of their imagined cliff, and they hail every momentary dip in production due to acute economic or supply disruptions as the beginning of the end of oil.

Apologists have tried to excuse Hubbert's poor fit with U.S. production data after 1970 by saying he could not have anticipated Alaskan oil. But he probably also could not have anticipated the fact that the oil-saturated California coast he did include would soon be virtually barred from oil production for political reasons, and this would have reduced his production estimates. Another contrived effort to redeem Hubbert's prediction consists of ignoring all production that falls outside a recently invented narrow categorization of "conventional oil." Some define conventional oil by its extraction methods (migrated crude in shallow terrestrial reservoirs accessed with vertical rigs). Others define conventional oil by its viscosity and the characteristics of the oil-bearing rock (API gravity >10, porosity > 5%, permeability > 10 millidarcies). Peak Oil theory is thus supposedly excused from failing to address the flood of new, light, sweet crude being produced by directional and horizontal wells from terrestrial source rock and ultra-deep offshore reservoirs. Earlier generations of oil producers would have viewed conventional oil differently as the years marched on and technology progressed. Conventional oil for thousands of years would have been asphaltic bitumen in surface pools or sand formations. For much of the 19th century, it would have been oil produced from human-powered drilling of wells less than 100 feet deep and east of the Mississippi river. Even using the modern and specious categorization of "conventional oil," there is no evidence of a peak or cliff in global crude production, but rather continued responsiveness to capital investment. So obvious has been the absence of the predicted scarcity that many governments and activist organizations are now frantically trying to figure out how to pile on new regulatory and tax burdens to keep oil production and consumption from accelerating further. Concern about scarcity has been replaced by concern about how to "keep it in the ground."

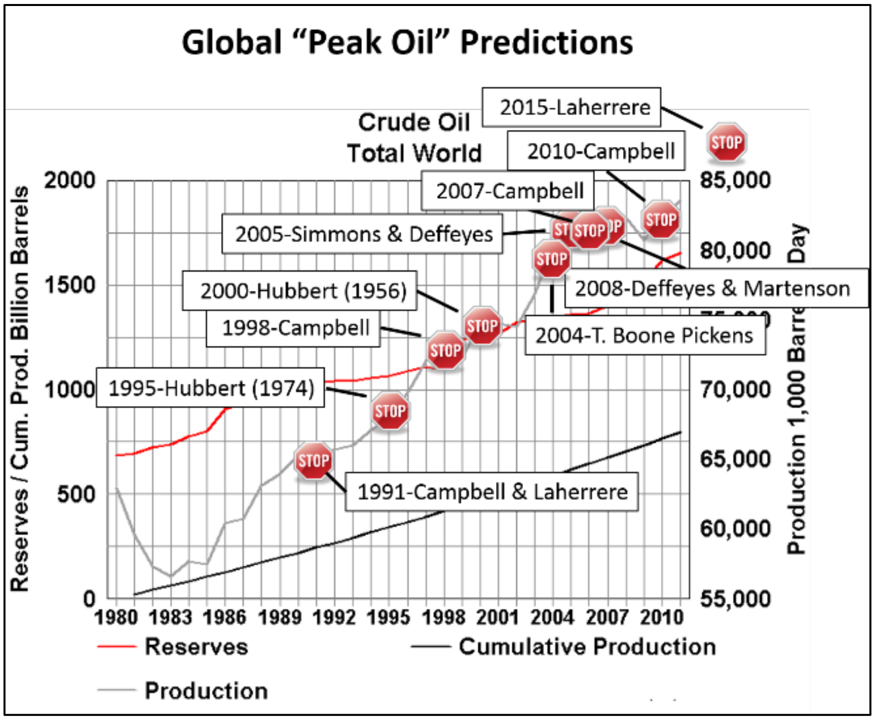

Figure 4 – Global Peak Oil Predictions

A New Curve

Rather than trying to patch up the Hubbert theory, it is past time to reconsider the assumptions and choose a better curve. The better curve is the classic sigmoid, also known as the *logistics curve*. The logistics curve is one of the most ubiquitous naturally-occurring mathematical forms in science and nature, empirically emerging as titration curves in chemistry, population growth curves in biology and demographics, and market penetration curves in economics, to name but a few. The math of the logistics curve is very similar to the Hubbert curve, but it substitutes ***P*** (the rate of production) for ***Q*** (the quantity of production), where ***P*** = ***dQ/dt***. In other words, the logistic function is essentially the integral of the symmetric sigmoid – where Hubbert's curve was limited in maximum *quantity* of production, the logistic function is limited in maximum *rate* of production. So the first term in the logistics equation produces exponential growth in the rate of production, and the second term sets a maximum boundary on the rate of production. Instead of total oil production being limited by Q_{max}, oil production rate is limited to P_{max}, which in logistics terminology is known as a *carrying capacity*. Such natural limits to growth often appear in complex systems with many interdependent variables.

Whereas Hubbert was modeling only the throttling effect of a single variable (i.e., scarcity of oil), real life is much more complicated. Production of oil is a function of many things other than oil: capital, labor, mineral rights, exploration technology, extraction technology, refining technology, geopolitical stability, trade barriers, economic stability, demand, market competiveness, substitution, etc. At any moment in time and any particular location, any one of these might be the ultimate limiting factor. And in the aggregate, factors other than scarcity of crude oil appear to dominate. In fact, other factors seem to be so dominant that crude oil production appears to follow the trajectory of a renewable resource, with reserves and production still continuously growing to fill petroleum's niche share of the global energy market.

When applying the logistics function in the field of population growth, it is understood that people themselves are a renewable resource, and the asymptotic limit occurs where balance is achieved between birth and death rates. In oil production, the natural emergence of the logistic curve and its approach to a sustainable limit seems to describe a dynamic balance between new well development and existing well decay, rather than the exhaustion of oil. There is no need to attribute this limit to any single factor – it is most likely a confluence of many factors that have in the past and will continue in the future to constrain oil production across time and geography. Biology and physics themselves are powerful constraints.

Biophysical Limits to Growth

The best conception of human civilization is as a giant collective organism. We happen to be an autotrophic organism that uses technology to make food (high-quality, readily assimilable energy) from crude resources in the environment. We have learned from studying the physics of living things that there are *biophysical* constraints on the size and density of organisms that arise from bottlenecking of energy and waste flows. It is fundamentally a geometry problem. As a creature grows larger, its demands for food and production of wastes scale up in proportion to its mass, which scales as the cube of its size. However, energy and waste are exchanged across membranes (lung walls, air intake screens, heat exchanger surface area) and through tubes (e.g., blood vessels, pipelines) whose cross-sectional areas scale as the square of size. Thus the demands for energy and waste flows increase with size at a higher order than the means to satisfy them, and this creates natural, internal, structural barriers to growth – i.e., *carrying capacity* limitations. These limits exist even if the energy sources and waste sinks external to the organism are unlimited. This straightforward power and waste engineering challenge is what limits the size of termite mounds and cruise ships. It follows that continued growth depends upon ever more concentrated fuels and wastes.

Concentration of energy is measured in metrics of energy density, power density, and energy return on investment (EROI). Each of these attributes of energy has power to constrain the growth of civilization and its resulting demand for oil. And the actual trajectory of the growth of civilization and its energy appetite so far indicates that these broad energy factors in general, rather than oil scarcity in particular, are indeed what is shaping growth. The interdependence of growth with energy density, power density, and EROI also explains why the progress of civilization has been in step with migration to ever more high-performance energy sources. We have moved from agriculture (annual harvestable power density of ~ 1.0 Watt per square meter of land cultivated) to the Wright Flyer (110 Watt/kg of gasoline and engine) to the Space Shuttle (10,200 Watt per kg of LH_2, LO_2, and engine). And it is why biofuels and PV solar and wind turbines, with lower EROIs and far lower densities, cannot sustain existing developed nations at their current energy-intensitive standard of living without support from fossil fuels and nuclear power.

Follow the Data

Below is a logistics curve fit I did in 2012 for U.S. oil production data available at that time. I have since updated the data through 2015 (most recent available), but have had no need to adjust the curve. The logistics curve best fit to empirically match the data revealed a natural plateau for U.S. production of about 3.5 billion barrels per year (9.5 Mbpd). A positive and premature spike to that level in the early 1970s was explainable by a set of special circumstances including a surge in Vietnam, the Apollo program, record cold winters, and the oil embargo. Alaska oil production, rather than being an anomaly, actually appeared to be a natural progression that fit the curve perfectly. A major break with the curve occurred in 1986, which was a year when the global oil market belatedly recognized a glut of overproduction, and prices collapsed for a period that would last 17 years until 2003. U.S. domestically produced oil, made uncompetitively expensive by the world's most restrictive drilling policies and environmental regulations, could not compete, and market share quickly dwindled even as global production and consumption continued to rise. And the oil not produced in the USA was displaced by imported oil, much of it the fruit of U.S. oil company investment overseas. Thus the dip in the curve was more about market share and EIA accounting limitations (no data tag to denote overseas oil production that is the fruit of U.S. foreign investment) than about domestic crude oil scarcity. However, a coming revolution in domestic production would indeed show up in the data.

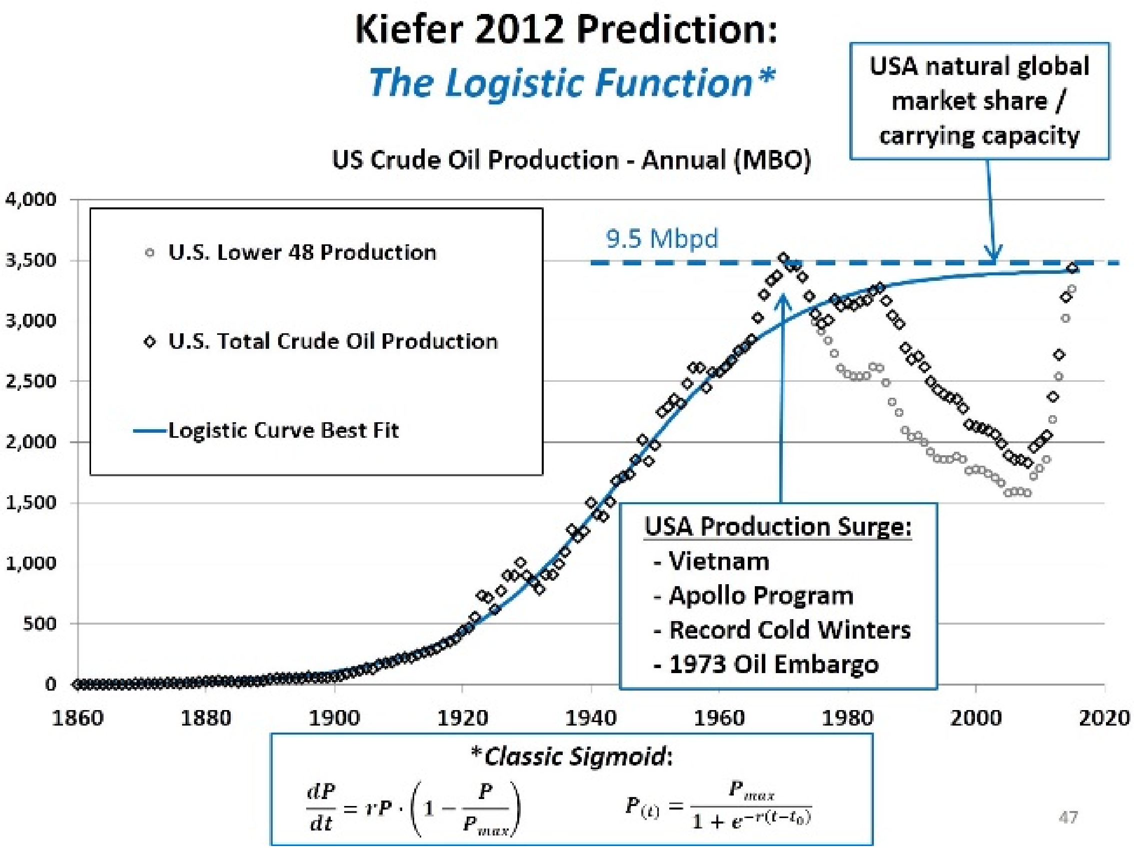

Figure 5 – Kiefer Curve

Based on 3 previous boom and bust cycles in global production in the 20th century, it was clear that it was only a matter of time before the march of U.S. technology would improve oil exploration and production efficiency enough to again make U.S. domestic production competitive and recapture market share. In fact, this was already well underway in the form of a massive wave of capital investment by the world's remaining privately held oil and gas companies benefiting from the rising prices accompanying another cycle of perceived scarcity that had arrived in 2003. As had happened many times before in its history, panic about the end of oil helped create profit margins that financed the investments that renewed the supply. By 2006, all of the technologies that enabled the fracking revolution were already fielded (3-D seismology, directional and horizontal drilling, sophisticated bore-head sensors and real-time telemetry, bore cementing and sequential perforation, hydraulic fracturing, advanced drilling fluids and proppant, etc.). Additionally, the first commercially successful ultra-deep "pre-salt" offshore well in the Gulf of Mexico was drilled in 1993, and by 2006 similar wells were being drilled off Brazil, ushering in another revolution of less notoriety but likely equal import with fracking that has yet to really make itself felt. Both of these revolutions depend upon specific technology and expertise for which the USA is unsurpassed. The stage was set by 2010 for U.S. oil production to come roaring back. The trend lines in 2012 indicated that U.S. production would reach the logistic curve carrying capacity of 9.5 Mbpd sometime before the summer of 2016.

In January of 2014 I specifically predicted a price collapse to $50-$60 bbl approaching this natural limit. According to EIA data after the fact, U.S. crude oil production hit 9.0 Mbpd in September 2014 and peaked at 9.6 Mbpd in April of 2015. WTI Cushing spot price peaked at $108/bbl in June of 2014 before beginning the plunge that would see prices below $50/bbl by January 2016. Current U.S. production is stable at 8.8 Mbpd. I expect to see U.S. production remain at or a bit below the 9.5 Mbpd limit, though not dip as low as it did following the 1986 glut. This is because most global oil companies have now been nationalized and foreign innovation and technology migration is thus slower today, allowing the USA to maintain a more enduring competitive advantage and preserve more market share. Private land and mineral rights ownership is also key to the economics of oil and gas, and this almost exclusively favors the USA as well. I don't believe perceived scarcity will again come into play to significantly boost prices for well beyond a decade. Of course the global market is always susceptible to short-term spikes from geopolitical crises.

The Global Carrying Capacity for Crude Oil

We have already seen that Hubbert's prediction for U.S. oil production was pessimistic and completely failed to predict our current condition. His prediction for global production was equally flawed.

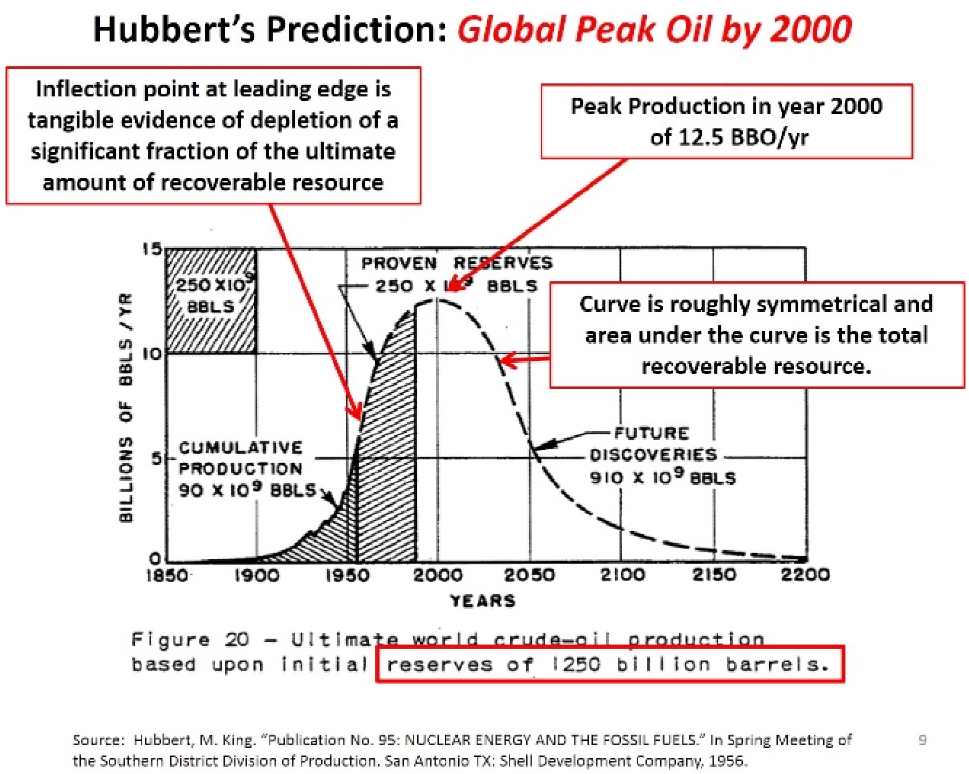

Figure 6 – Hubbert's Global Oil Prediction

According to Hubbert's prediction, 2017 global crude oil production should be 12 billion bbl/yr and falling irretrievably. Instead it is over 30 billion bbl/yr and climbing steadily. And while oil is now being more properly priced as a premium transportation fuel and industrial feedstock rather than as a bulk combustion fuel, there is still an unquenchable thirst for this commodity in the developing world representing a huge latent demand. Applying the same logistics curve fit technique to global production data is illuminating.

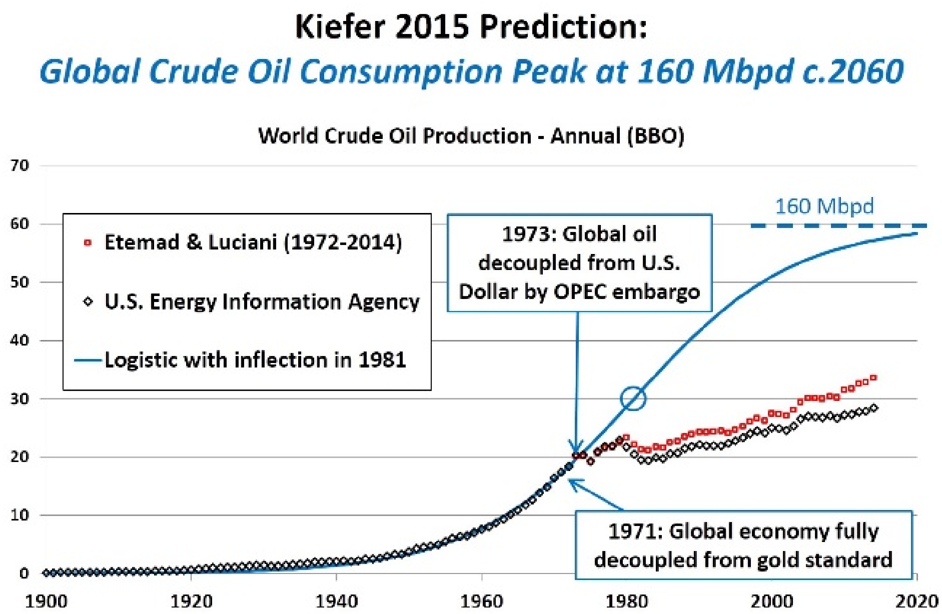

Figure 7 – Kiefer's Global Oil Prediction

If trustworthy, this logistic curve shows that global production and consumption are only halfway to the natural plateau. You can see in the figure some reasons for why progress may have departed from the ideal curve to a more linear path of growth. These factors include international market dysfunction beginning in 1971 due to U.S. abnegation of Bretton Woods and the subsequent global transition to pure fiat currencies and floating exchange rates, the emergence of the OPEC cartel, socialist evolution of western nations leading to crippling debt and tax burdens, nationalization of reserves and oil companies, implementation of restrictive environmental regulations and anti-energy policies, etc. The fiscal economy of the entire globe is way over-leveraged and is operating with a huge debt drag on it. All ability to stimulate economies with monetary policy and cash injection has been exhausted by the governments and central banks. The only way out now is for a massive influx of cheap energy to cause a surge in the creation of goods and services that will elevate the real gross world product to catch up with the global money supply, and thereby reduce the leverage. Right now, the USA seems to be uniquely positioned to benefit from the cheap energy revolution of fracking, while pre-salt hydrocarbons may be more globally accessible.

Nevertheless, continued growth in global production toward the predicted carrying capacity is my prediction – one which will not bring much comfort to those who demonize CO_2 and think the Earth is on the knife edge of climate catastrophe. I'm not sure which nations will be contributing which fractions to this production plateau, but I believe it will come to pass. Even if the world added a new 2,000-megawatt nuclear plant every week for the next 50 years, we would not displace the need for this energy, particularly for air and sea travel, when the growing demand of developing nations is considered. Fortunately, fossil fuel energy has proven an excellent resource for helping civilizations cope with a host of threats. Hydrocarbons excel at reducing human exposure to and harm from severe weather, and in making crops much more fruitful and far less dependent upon the vagaries of nature. Climate change adaptation and mitigation would appear to be the only reasonable strategy going forward, as it has been for all of human history.

Finite v. Sustainable

If the logistic curve is indeed the better fit than the Hubbert curve, what does that tell us about the underlying commodity and the forces shaping its production? The essential difference between the two curves is that a Hubbert curve describes a finite resource whose production is being choked down by scarcity, while a logistics curve describes a sustainable resource who production is stabilized by any of a host of natural limiting factors at a level below which scarcity comes into play. The question of finite v. sustainable is really where the prevailing worldview is most challenged.

For oil to appear to be a resource that can be sustainably consumed, there are two possibilities. First is the case that the amount of ultimately producible oil is very, very large compared to its stabilized consumption rates, and essentially dwarfs demand, so that true scarcity will not be a factor for a very long time. A second possibility is that oil is indeed a renewable resource, and that the geologic processes that created the oil already extracted are still at work creating more at a significant rate compared to consumption – there is the potential for balance between demand and supply. A combination of these two is also possible. Experienced petroleum geologist and geophysicist David Middleton recently submitted an excellent online essay on what is known and theorized about the thermogenic processes that produce oil. He makes a point about how much reservoir quality sedimentary rock there is in the oil and gas zones of the Earth's crust. The amount is so vast that every millionth part of it can hold 100 billion barrels of oil, though we really don't know how much of it is charged with oil. Additionally, there is no reason to assume that the Earth is not continuing to cook more crude oil from existing kerogen in the crust. Pre-existing oil and kerogen may be enough to sustain the logistics curve of consumption for generations, or for millennia. If there should prove to be any truth to the controversial theory of abiotic oil formation from rock and seawater in the deep crust, this would only add to the Earth's endowment of hydrocarbons available to man.

There are other reasons why I hold to the sustainable oil view, including my own research and analysis of fossil fuel energy return on investment (EROI) and oil production versus drilling effort. An essential part of this analysis that many get wrong is to ignore the often lengthy delay between oil industry capital investment and ROI. During the crisis window of perceived scarcity, there is much capital investment and negative cashflow as a flurry of wildcatters chase prospects. Once the glut is recognized, the capital investment dries up and there begins a lean period of low prices which includes a painful battle for market share and brutal consolidations, as most of the wildcatters fold up and are absorbed by larger companies with more fat to live on. Then finally comes a long period of steady, profitable production from reserves that seem to miraculously grow and grow without much further investment – this is the payback period that is usually ignored because the crisis is long past. Any ROI or EROI analysis that does not include the full bust-and-boom cycle will yield false results. When the accordion-effect lag between capital investment and ROI is properly considered, U.S. oil production EROI has remained above 10:1 for its entire commercial history, except for brief dips associated with recessions. Oil yields today are still about 40 barrels per foot drilled, the same as in the mid-1980s, only now we are drilling horizontally as well as vertically. If scarcity starts to rear its head as an emerging force in shaping oil production, we should first see it in irretrievably falling EROI and yield per foot.

The ultimate limiting factor for energy consumption is human population. The good news is that birthrates continue to fall, and they fall the most where energy intensity is highest. This is another self-regulating externality not accounted for in Hubbert's theory. The worst-case prediction from the U.N. today is a peak of 11 billion people by 2100. Based on the trend lines of energy and other resource consumption, that appears to be within the carrying capacity of the Earth as enabled by evolving human technology. I believe a strong case could be made that more rapid economic development of underdeveloped nations using the highest EROI energy available would lead to a lower peak population and a smaller perpetual burden on the Earth's resources. This is exactly the opposite of what restrictions on CO_2 emissions are achieving by putting the brakes on development. The correct worldview of energy is essential to making good energy policy and genuinely helping humans and the environment. The evidence is that crude oil today remains a plentiful and high-performance resource with considerable prospects to grow in production and consumption for another century.

About the Author

Captain Todd "Ike" Kiefer, USN (ret.) is director of government relations and economic development for East Mississippi Electric Power Assn. and president of North Lauderdale Water Assn. His career in public utilities follows 25 years as a naval officer and aviator. He has degrees in physics, strategy, and military history, and diverse military experience that spans electronic warfare, nuclear submarines, operational flight test, particle accelerators, Pentagon Joint Staff strategic planning, and war college faculty. Deployed eight times to the Middle East and Southwest Asia, spent 22 months on the ground in Iraq. Commanded Al Asad Air Base and Training Squadron NINE. Author of several published papers on energy security and biofuels.

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