The Coal Question and Climate Change

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This is a guest post by Dave Rutledge, Chair for the Division of Engineering and Applied Science at Caltech, which has 12 departments with 75 faculty members and 500 graduate students.

Dave is fascinated by the possibility that the key to understanding the future of world coal production may be in the history of the mining areas in the northern Appalachians and the north of England. Dave is also interested in the question of how California will make the transition from fossil fuels to renewable fuels for electricity production.

At The Oil Drum, there has been much discussion of the modeling of future oil production and the reliability of reserve data. It is also understood that burning fossil hydrocarbon fuels increases the CO_2 concentration in the atmosphere, and that this is likely to affect our climate. What about coal? Can we figure out how much coal is likely to be produced, and how quickly the coal reserves will be exhausted? How reliable are coal reserve numbers? What can our models for coal and hydrocarbon production tell us about atmospheric CO_2 concentrations? About climate? It turns out that we can give answers to all of these questions, using the same Hubbert linearizations and normal curve fits that we use for oil.

The importance of these approaches to estimating future production is emphasized by this astonishing statement in the pre-publication version of the National Academy of Sciences Report on coal, released yesterday:

> Present estimates of coal reserves are based upon methods that have not been reviewed or revised since their inception in 1974, and much of the input data were compiled in the early 1970s. Recent programs to assess reserves in limited areas using updated methods indicate that only a small fraction of previously estimated reserves are actually minable reserves.

I appreciate this opportunity to contribute a post to The Oil Drum. This site is the most important forum for the discussion of oil production, because of the vigor and depth of the debate. I would like to offer some calculations for coal production and climate change. I hope you that find coal as interesting as oil. Coal is the most important fossil fuel for generating electricity, and it is a major source of atmospheric CO_2.

Oil reserves are rightly viewed skeptically at The Oil Drum, in large part because of fraud by the OPEC countries. Coal reserves are compiled by the national geological surveys, and unlike oil reserves, they are honest. However, recently Dr. Werner Zittel and Jorg Schindler and their

Energy Watch Group have written an important paper "Coal: Resources and Future Production" that shows that there are major problems with the reliability of coal reserves, and indicates that the reserves may be too high. Coal is different from oil, and much of the intuition that we may have developed about oil from nights pondering TOD posts is wrong for coal. Finding oil is hard, and we have not found it all yet. In contrast, people knew where the coal was a century ago. Once oil is found, it is likely to be produced quickly, so much so that discovery history is routinely used to predict future production. On the other hand, there are large coal fields that are almost undeveloped. As an example, Montana has larger coal reserves than Europe, Africa, or South America, but it is producing less than 0.1% of that coal each year. Our estimate of future coal production depends a lot on whether we think that the people of Montana will get into serious coal production. Finally, in contrast to the situation for oil, the world market for coal is only partially developed. Most coal is consumed in the country it is produced in, and there are large differences in prices, even in the same country. For this reason, we will analyze production on a regional basis. I will apply the techniques to coal that are routinely used here for oil, and consider the consequences for future climate change. People who are interested in more details can get the spreadsheets with the raw data at my web site, with lots of additional figures and source links.

The authoritative source of information on climate change is the UN Intergovernmental Panel on Climate Change (IPCC), which is releasing its 4th Assessment Report this year. This is a mammoth undertaking, with more than 1,000 authors and more then 1,000 reviewers. The fossil-fuel contribution to climate change is considered in terms of 40 scenarios, each considered to be equally valid. In the assessment modeling, the factors for future fossil-fuel production are primarily population, policy, and GDP, and limitations in fossil-fuel supplies are not considered critically. Parts of the scenarios would strike most readers at The Oil Drum as preposterous. For example, in 17 of the scenarios, world oil production is higher in 2100 than it was in 2000. Even OPEC oil ministers do not make that claim.

Thinking about climate change also requires adjusting to the long time scales. At the Oil Drum, there is much discussion of whether the Ghawar field will decline next year. However, from the point of view of a temperature peak in the next century, it matters little whether we burn a ton of coal now or 50 years from now. This means that a policy that results in a ton of coal being consumed next year instead of this year does little good. Because of the long time horizon, we will use cumulative plots, which smooth out the year-to-year fluctuations. To start with a plot that you will probably recognize, let us consider the cumulative production for US crude oil, courtesy of the amazing data gnomes at the EIA. This is a terrific series that starts all the way back in 1859. On the same graph, I have a shown a normal curve, fit to the data. This is the bell-shaped curve from statistics class, plotted in cumulative form. The fit is done just by clicking the Solver button in Microsoft Excel, and it is absolutely perfect. I used 3-point symbols, which are the smallest ones I could see, and the symbols bury the fitted curve for over 100 years. We will see that we can also use cumulative normal fits for coal production.

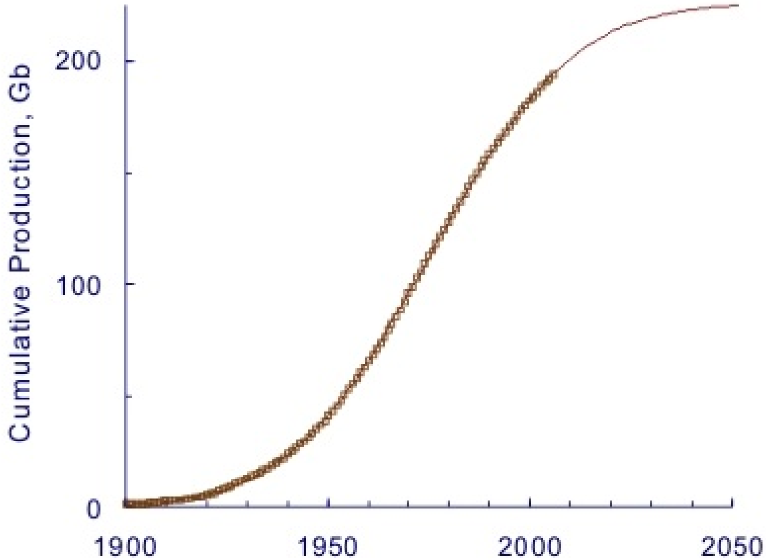

Figure 1. Cumulative US crude-oil production from 1859, plotted from 1900 on, together with a normal curve that is the least mean square fit (ultimate 225Gb, 10% year 1939, 90% year 2011). The projected remaining production is 31 billion barrels. Given current production levels of 2 billion barrels per year, the prognosis for US oil production is grim.

Often we do not have enough data to fit for remaining production this way. In these situations, I will use a Hubbert linearization to estimate the remaining production, like we often do for oil. Hubbert introduced this approach for modeling oil production in "Techniques of Prediction as Applied to the Production of Oil and Gas," in Saul I. Gass, ed., Oil and Gas Supply Modeling, pp. 16-141. National Bureau of Standards special publication 631. Washington: National Bureau of Standards, 1982. This is a great paper. It is difficult to find, but you can download it here (15MB file). Figure 2 shows a Hubbert linearization for world hydrocarbon production. The trend line is for 3.2 trillion barrels of oil equivalent (Tboe) remaining. We will use this number for our simulation of future atmospheric CO_2 concentrations and temperature rise. This is 20% larger than the reserves given by the German resources agency BGR, 2.7Tboe. The BGR includes 500Gboe for unconventional sources. In contrast, the IPCC assumes that 11-15Tboe is available for production for its climate-change scenarios.

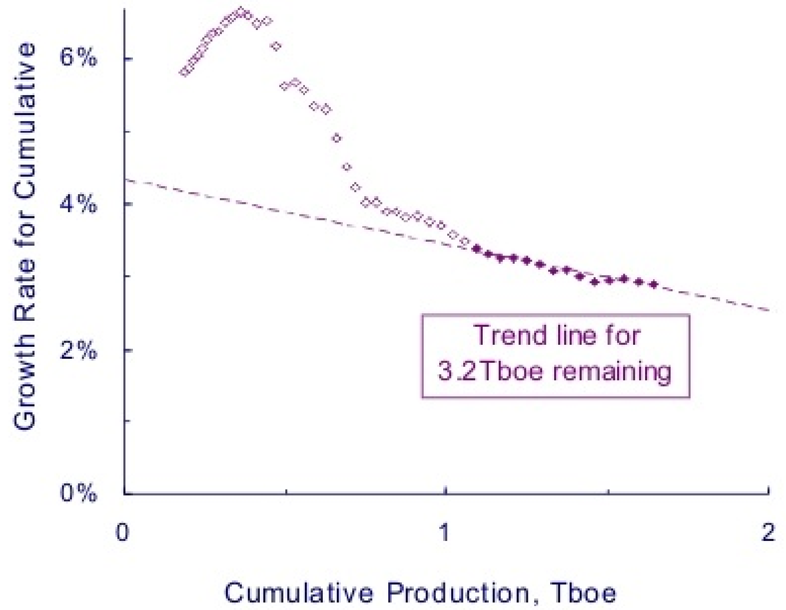

Figure 2. Hubbert linearization for world hydrocarbon production (total of oil, natural gas, and natural gas liquids), based on production data from the [2007 BP Statistical Review](). Open symbols 1960-1992, closed symbols 1993-2006.

For coal, we start with the United Kingdom. The British production cycle is nearly complete, and it is substantial, equivalent in energy content to the cumulative Saudi oil production. There are excellent production records back to 1854, and there is even a good cumulative production figure for 1853. The Victorians were outstanding geologists, and there are good reserve estimates back to 1864. British coal even had a Hubbert. His name was William Stanley Jevons, and he was an economist. In 1865, he wrote a book, *The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-Mines* , which should be read by anyone who is interested in coal or oil. Jevons wrote that even though the reserves-to-production (R/P) ratio was around 1,000 years, exponential growth would exhaust British coal in the 20th century. Jevons was right. In his time, there were more than 3,000 coal mines. Now the British are down to six major underground mines, with the last Welsh mine, the Tower Colliery, due to finish off its last seam next year. Figure 3 shows a Hubbert linearization for British coal. There is a good trend line, and the very first point in 1854 is near the line. We will see that the quality of the trend is in contrast to the reserves, which badly over-estimate remaining production throughout.

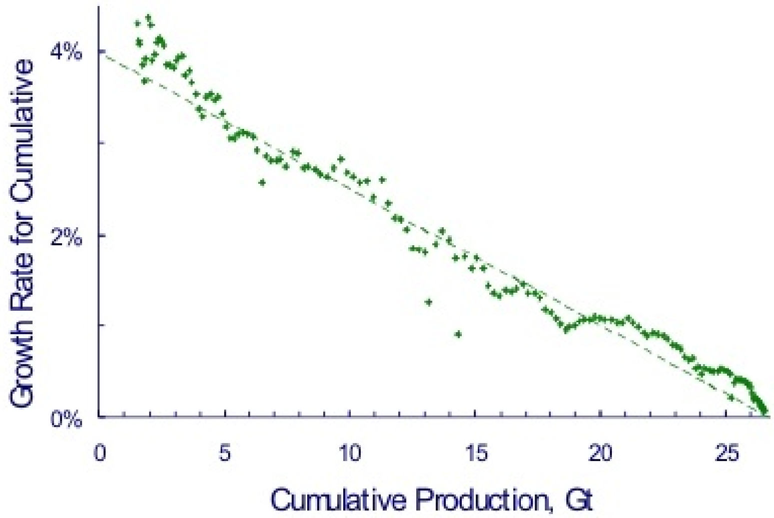

Figure 3. Hubbert linearization for British coal from 1854 to 2006, with a trend line for an ultimate of 27Gt. The peak production was 292Mt in 1913. The production for 2006 was only 19Mt.

The normal fit, shown in Figure 4, is more complicated than our normal fit for US oil. There are two pieces, one for production before the Second World War, and one afterwards with a higher ultimate. Why did this happen? It could simply be that economic activity increased after the war. Another possibility is technical change; strip mining started in Britain during the war. Yet another possibility is that it is a result of the coal mines being nationalized in 1947. This created strong political incentives to support coal production. I was an undergraduate student in England in the early 70's when the coal miners brought down the Heath government. Even though the mines are privately owned now, the mining companies still receive government grants to help open up new seams.

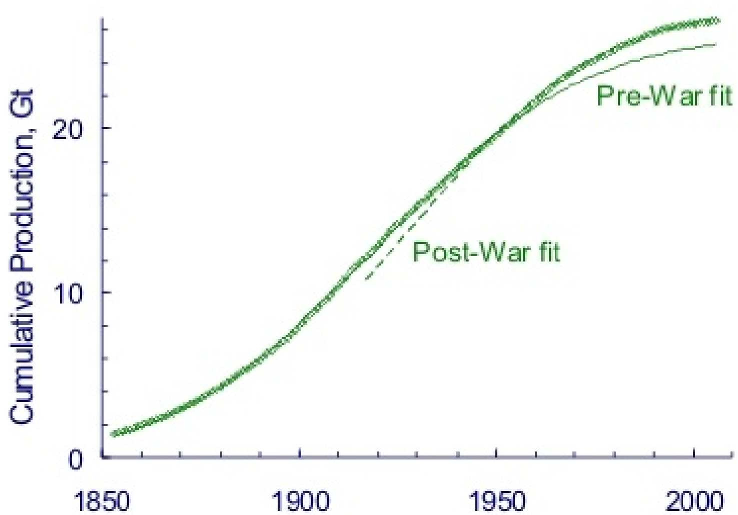

Figure 4. Cumulative normal fits for British coal. The pre-war fit gives an ultimate of 25.6Gt, with the 50% year in 1920. The post-war fit gives an ultimate of 27.2Gt, with the 50% year in 1927.

Now that British coal production is essentially done, we can compare historical reserves with the actual remaining production, which we now know. Jevons discusses a reserve calculation done in 1864 by Edward Hull. Hull made allowances for coal left in the pillars that stabilize the mines against collapse, for bands of coal around the outside to keep out water, and for areas where the seams became thin. Figure 5 shows reserve estimates made at different times, compared with a plot of remaining production. Notice that the reserves are way too high, and that they collapse near the end of the production cycle. This is a major problem if you want to use reserves to predict production. Reserves should be an indicator of future production. Unfortunately it appears to be the other way around.

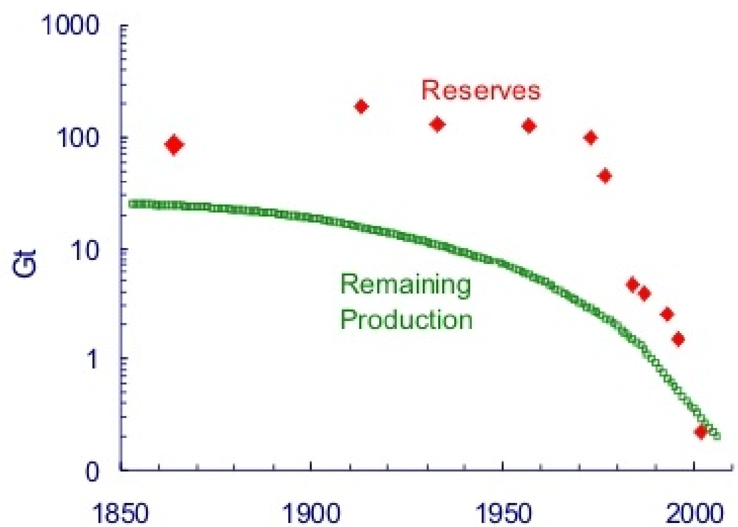

Figure 5. Reserves compared with remaining production for British coal. Note that this is a logarithmic plot, so the differences are larger than they may appear. The reserves are taken from the World Energy Council series of reports. These are hard to track down, but you can download them here (50MB).

Now let us consider the reserve history with the traditional R/P ratio. Figure 6 is a plot of the R/P ratio over time, beginning with Hull in 1864. The R/P ratio started at 900 years, and stayed above 500 years until a hundred years later. However, the R/P ratio collapsed in the 70's, dropping almost 749 years in 1973 to 90 years in 1984. In the end, only 30% of Hull's reserves were eventually produced. This underproduction is not an isolated error. On my web site, there are plots for Pennsylvania anthracite and Virginia bituminous coal. Pennsylvania anthracite has a single trend line with a single normal fit. Virginia bituminous has pre-war and post-war fits, like

British coal. In each case, the remaining production was only 16% of the early reserves. And in other cases I have considered, where a clear trend exists, the remaining production is less than reserves. We will consider the reserves to be an upper limit on remaining production.

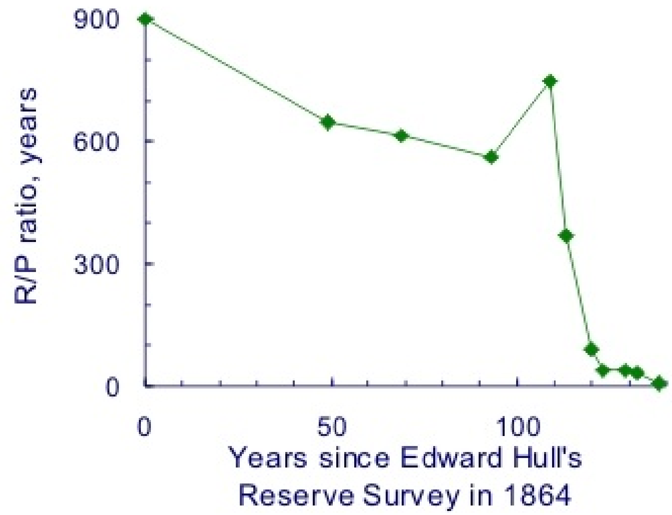

Figure 6. Reserves-to-production ratio for British coal. The R/P ratio has not been a good indicator of future coal production.

I approach the problem of estimating future world coal production by breaking the world up into eight regions, and estimating considering production in each separately. The regions are Australia, South Asia, East Asia, Former Soviet Union, Africa, Europe, South America and North America. North America is further divided into Eastern US, Western US without Montana, Montana, Canada, and Mexico. We look for trends, and if we find them, we will use them to estimate remaining production. If there are no trends, we will use reserves. Because of space limitations, I show plots for only two regions here, but the rest are on my site, along with the data sources. Figure 8 shows a Hubbert linearization for coal east of the Mississippi. The production data come from an outstanding USGS collection developed by Robert Milici, which gives production data by state back to 1800.

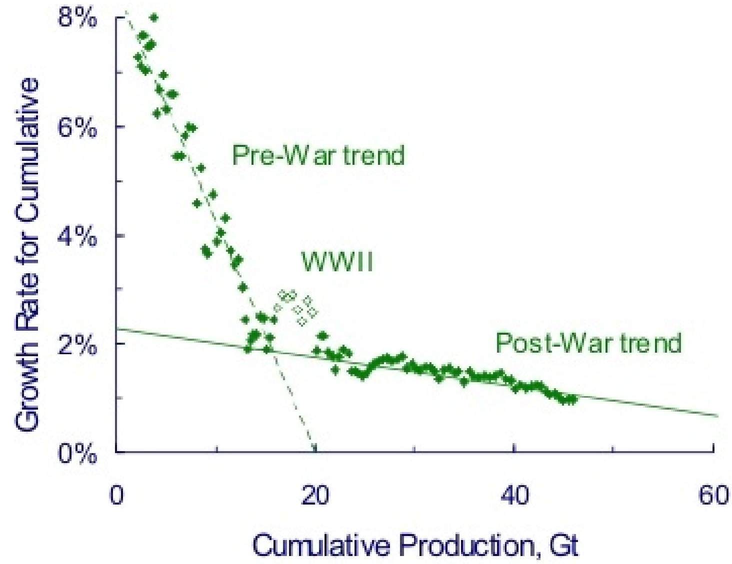

Figure 7. Hubert linearization through 2005 for US coal east of Mississippi, without Pennsylvania anthracite. Early closed symbols 1900-1940, open symbols 1941-1945, later closed symbols 1946-2005. There is a pre-war trend for an ultimate production of 20Gt, and a post-war trend for 40Gt remaining. The reserves are 96Gt, reported by the EIA.

Figure 8 shows the Hubbert linearization for China. China accounts for 40% of the world's coal production and is producing more than twice as much coal as the US. For 40 years, there has been a trend for 70Gt remaining, but in the last three years, production has gone through the roof. There may be a move to a new trend line underway. It is also possible that production will come back to the original trend line. During the Great Leap Forward from 1958 to 1960, reported production soared for a few years, but returned afterwards to previous rates.

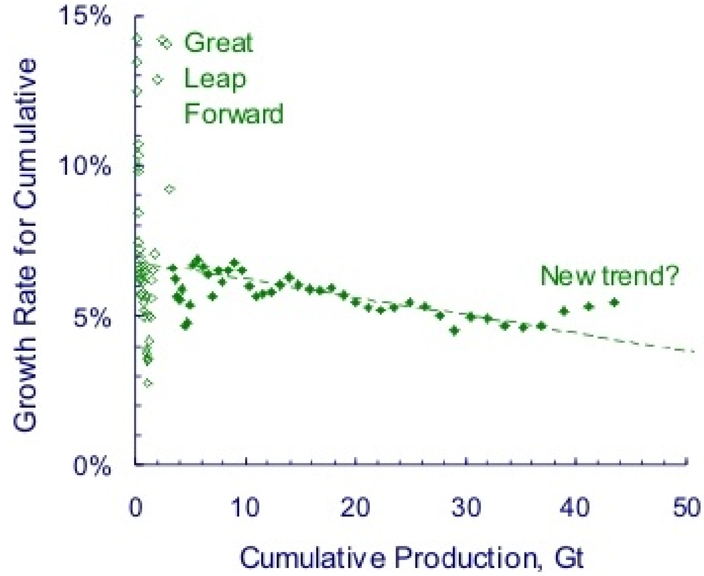

Figure 8. Hubbert linearization for Chinese coal. Open symbols 1918-1961, closed symbols 1962-2006. The trend for 70Gt remaining compares with reserves of 189Gt, reported by the Chinese Ministry of Land and Resources. I am grateful to Sandro Schmidt of the BGR for sending me this reserve information.

The table below shows the results for the different regions. For South Asia, and Central and South America, there has been exponential growth in recent years, so there is no trend. For these regions, I used reserves, which are likely to be too high. For the former Soviet Union, there is the opposite kind of problem. Production still has not returned to Soviet-era levels. I used the trends from the Soviet era, which may be pessimistic. North America is a patchwork, with trends for the East (40Gt), West (25Gt), reserves for Montana (68Gt), and trends for Canada and Mexico (2Gt total). The world total is 435Gt, 1.6Tboe if we convert at the current energy density of 3.6boe/t. This is about half the reserves of 963Gt (3.5Tboe). Both are much lower than the amount that is assumed to be available for the IPCC scenarios, which is 18Tboe. It is possible that some of the trends will turn out to be too low, because of the possibility of switching to a new trend line, as the British did after the war. On the other hand, where we have used reserves, we are likely to be too high, and this will offset underestimates elsewhere. I am using my judgment to arrive at the solution, and your judgment may differ.

Region	Reserves Gt	Trends Gt
North America	255	135
East Asia	190	70
Australia and New Zealand	79	50
Europe	55	21
Africa	30	10
Former Soviet Union	223	18
South Asia	111	
Central and South America	20	
World (at 3.6boe/t)	963 (3.5Tboe)	435 (1.6Tboe)

Table. Reserves vs trends for remaining production for coal. The reserves are taken from the World Energy Council 2004 report, except for China, where we used the reserves from the Chinese Ministry of Land and Resources by way of Sandro Schmidt, and South Africa, which has been reassessed recently

Figure 9 shows the cumulative plots for future-fuel production using the trends we have developed for hydrocarbons and coal, and with lms fits for the 10% and 90% years. The coal ultimate is about half the hydrocarbon ultimate.

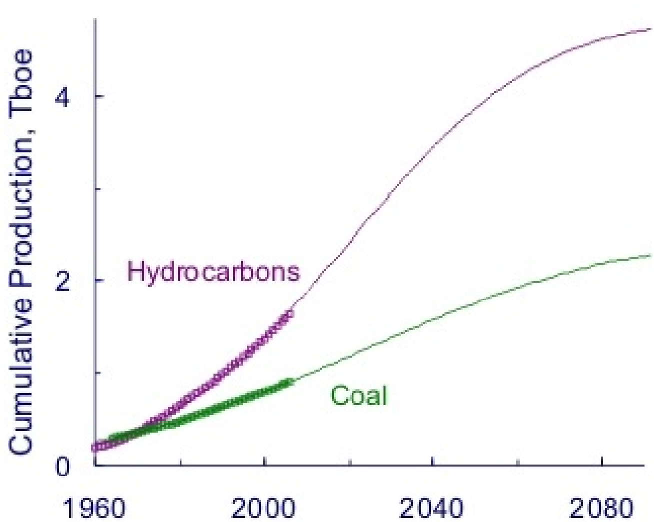

Figure 9. Cumulative fossil-fuel production with normal fits for hydrocarbons (ultimate 4.8Tboe, 10% 1975, 90% 2066) and coal (ultimate 2.5Tboe, 10% 1960, 90% 2088).

Now we are in a position to see what some consequences for climate are. We convert future hydrocarbon and coal production to atmospheric carbon emission using EIA coefficients and plot them as the Producer-Limited Profile in Figure 10, together with the carbon emissions from the 40 scenarios. The Producer-Limited Profile has lower emissions than any of the 40 scenarios. This would be true even if we calculated the emissions with the full coal reserves. Jean Laherrere was the first to call attention to this anomalous situation. He has made the point forcefully and repeatedly, to no apparent effect.

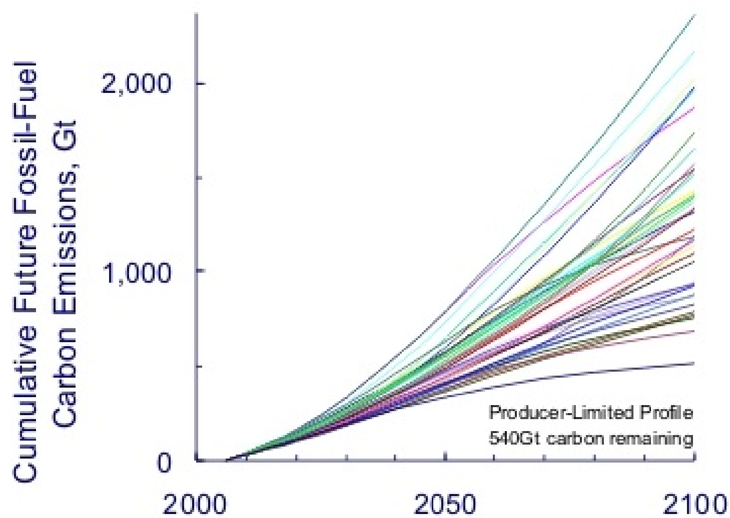

Figure 10. Future fossil-fuel carbon emissions for our Producer-Limited Profile, together with the 40 IPCC scenarios. The curves show a major defect of the IPCC scenarios - they are not defined past 2100. In many of the scenarios, fossil-fuel production has not peaked by then.

For climate simulations, I use Tom Wigley's program MAGICC. Tom and his colleagues at the National Center for Atmospheric Research (NCAR) have performed a wonderful service by making this program available online, so that anyone can try out different scenarios. I modified his WRE profiles to use our fossil-fuel carbon-emission levels. The W in WRE is for Wigley, and the WRE profiles were developed to target specific CO2 levels. One advantage of the WRE profiles is that unlike the IPCC profiles, WRE profiles are defined past 2100. In addition to our Producer-Limited Profile, I define one policy profile called Super-Kyoto, where future fossil-fuel production is stretched out by 50% (Figure 11). I am imagining a future agreement that is more successful in reducing the rate of fossil-fuel consumption than the present Kyoto Agreement, but that does not change the total remaining production. The Producer-Limited Profile gives a peak of 460ppm in 2070, while Super-Kyoto gives a peak of 440ppm in 2100. These compare with the current level of 380ppm and the pre-industrial level of 280ppm.

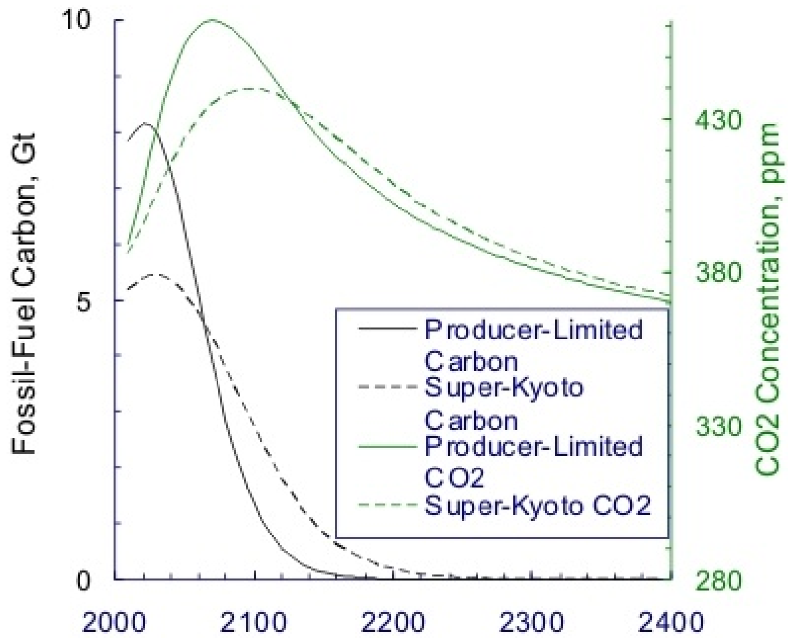

Figure 11. Carbon emissions and atmospheric CO2 levels. The atmospheric CO2 levels are calculated from MAGICC simulations.

Figure 12 shows the simulated temperatures. The maximum temperature rise for our Producer-Limited Profile is 1.8°C in 2150. The blue lower curve shows the part of the temperature rise that is associated with future fossil-fuel use. This is calculated by running the simulation with and without future fossil fuels, and subtracting. It turns out that the maximum temperature rise associated with future fossil fuel use is only 0.8°C, less than half of the total. This means that the contributions to the temperature rise from fossil fuels that have already been consumed, and from deforestation, and from other greenhouse gases amount to more than the contribution from future fossil-fuel use. The Super-Kyoto Profile does not decrease the maximum temperature. The reason for this is that the characteristic time for temperature change is much larger than the corresponding times for fossil-fuel exhasution. From a mathematical point of view, the system is an integrator.

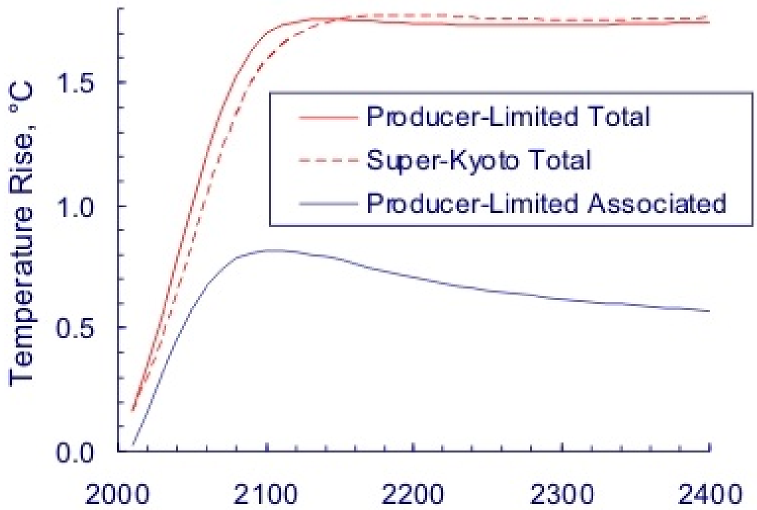

Figure 12. Simulated temperature rises from MAGICC simulations.

Based on these results, what conclusions do we draw? The projection for hydrocarbons is 20% larger than reserves, while the projection for coal is only half of reserves. Our Producer-Limited Profile has future fossil-fuel production that is lower than all 40 of the IPCC scenarios, so it seems that producer limitations could provide useful constraints in climate modeling. Stretching out production does not lower the temperature maximum. If we wish to reduce the temperature rise, we must bury the CO2 (assuming that it will not leak out for 1,000 years), or establish preserves for fossil fuels that prevent them from being produced. One possibility for fossil-fuel preserves would be US federal lands. One third of US fossil-fuel production is from federal lands, so remaining fossil-fuel production could be reduced substantially simply by letting the current leases run out, without establishing new ones.

Why are coal reserves high? In his book *Hubbert's Peak*, Ken Deffeyes says this about the US Geological Survey, "When USGS workers tried to estimate resources, they acted, well, like bureaucrats. Whenever a judgment call was made about choosing a statistical method, the USGS almost invariably tended to pick the one that gave the higher estimate." My theory relates to my sister-in-law, Nancy Yee. Nancy appraises apartments for a bank. If her estimates are too high, the bank loses money, and she loses her job. My suspicion is that no one in a geological survey ever lost her job for being optimistic about coal reserves

Could these projections be improved? Yes. I am still looking for coal-production histories for many countries before 1981, when the BP Statistical Review tables give out. The most important ones are the Soviet Union and South Africa. I would grateful if any readers could help me locate this data.