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Estimating long-term world coal production with logit and probit transforms

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ABSTRACT

An estimate for world coal production in the long run would be helpful for developing policies for alternative energy sources and for climate change. This production has often been estimated from reserves that are calculated from measurements of coal seams. We show that where the estimates based on reserves can be tested in mature coal regions, they have been too high, and that more accurate estimates can be made by curve fits to the production history. These curve fits indicate that total world production, including past and future production, will be 680 Gt. The historical range for these fits made on an annual basis from 1995 to 2009 is 653 Gt to 749 Gt, 14% in percentage terms. The curve fits also indicate that 90% of the total production will have taken place by 2070. This gives the time scale for considering alternatives. This estimate for total production is somewhat less than the current reserves plus cumulative production, 1163 Gt, and very much less than the amount of coal that the UN Intergovernmental Panel on Climate Change, or IPCC, assumes is available for its scenarios. The maximum cumulative coal production through 2100 in an IPCC scenario is 3500 Gt.

Contents

1. Introduction

In the preface to his 1861 treatise, *The Coal-Fields of Great Britain* (Hull, 1861), geologist Edward Hull wrote, "Conscious of many defects, I am fain to hope that these pages will be found to accomplish faithfully the great object desired, – to give the public an answer to the oft-repeated question, "How long will our Coal-fields last?" Hull analyzed British coal fields, and arrived at "an available quantity of 79,843 million [long] tons, which if divided by 72 millions of [long] tons (the quantity raised in the year 1859 nearly), would last for no less than 1100 years." For his assessment, Hull included seams of thickness two feet or more, down to a depth of 4000 feet. Hull's estimates were later raised by a Royal Commission on Coal Supplies in 1871, which counted seams down to a thickness of 1 foot, and arrived at 149 Gt (billion metric tons) of minable coal (Royal Commission, 1871).

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One hundred and fifty years have now passed. Fig. 1 tells the story of British coal production since Hull and the Royal Commission. Production peaked in 1913 at 292 Mt (million metric tons). The following year, 40% of the miners of military age volunteered for service in the First World War (Supple, 1987), and production never again reached this level. There was a temporary rise after the mines were nationalized in 1946, and a comparable fall before the mines were privatized in 1994. This reflects large government investments during the early nationalized years, and the closing of many mines in the years before sales to private owners. Production in 2009 was 18 Mt, only a quarter of the 1859 production. The last time British coal production was this low, Napoleon was alive. When Welbeck Colliery finished production in May 2010, only five collieries with producing longwall faces remained: Daw Mill, Hatfield, Kellingley, Maltby, and Thoresby. For comparison, there were 803 producing faces in 1973 (Ashworth, 1986). This production collapse was a not a result of declining prices or a lack of demand. The pit price for British coal in 1859 was 5 shillings per long ton, which after adjusting for inflation, is 40% of the modern price of £47/t (Church, 1986; O'Donoghue et al., 2004; UK Coal, 2010).[1] Moreover, the size of the British coal market now, 49 Mt in 2009 (DECC, 2010), is not too different from what it was in 1859.

Thus we now know the answer to the question Edward Hull posed in 1861. British coal has lasted 150 years, not 1100 years. British mines have produced 27 Gt of coal, not Hull's 81 Gt nor the Royal Commission's 149 Gt. In retrospect, it is clear that both Hull's numbers and the Royal Commission's were not good estimates of production in the long run. It is also clear what was wrong with the estimates – the criteria were too optimistic. Nowhere in the world, then or now, are one-foot or two-foot seams routinely mined at 4000 feet.

We will see this under-production of reserves in other mature regions, the Pennsylvania anthracite fields, France and Belgium, and Japan and South Korea. In this paper, an alternative approach to estimating production in the long run based on probit and logit transforms of the production history is introduced. This approach gives better estimates of the long-term production for each of the mature regions than reserves. The approach is then applied to the active coal regions of the world, and an estimate for long-term world production is made by adding these estimates. As with the mature regions, this estimate turns out to be less than one made from reserves.

One application of these estimates is in making climate projections. The best known climate projections are those of the UN Intergovernmental Panel on Climate Change (IPCC). In the IPCC models, a substantial portion of the carbon dioxide emitted by burning fossil fuels will be in the atmosphere for centuries. This long time frame makes it important to have an estimate of coal production in the long run.

2. Theory

The curve-fitting process starts with the cumulative production, q_t, calculated at the end of year t. Let us define the exhaustion e_t as

$$e_t = q_t / Q \tag{1}$$

where Q is a long-term production estimate. Two s-curve models for the exhaustion are used, the logistic and the cumulative normal. The logistic model is given by

$$e_t = 1/(1 + \exp[(t_{50} - t)/\tau]) \tag{2}$$

[1] Britain's largest coal producer, UK Coal, reported an average selling price of £1.87/GJ for 2009 in its annual report (UK Coal, 2010). In the report, UK Coal gives the energy density as 25.121 GJ/t, so this price is equivalent to £47/t. The Office of National Statistics, the Bank of England, and the House of Commons Library have agreed on an index for making price comparison in different years (O'Donoghue et al., 2004). In the index, the purchasing power of an 1859 pound is reckoned at 79 times that of a 2003 pound. At 20 shillings to the pound and 0.98 metric tons per long ton, the 1859 price of 5 shillings per long ton is equivalent to £18/t.

Fig. 1. British coal production (Mitchell, 1998b, for production through 1980, and BP, 2010 for more recent production).

where τ is a time constant, and t_{50} is the year of 50% exhaustion. The cumulative normal model is given by

$$e_t = C((t - t_{50})/\sigma) \tag{3}$$

where C is the cumulative standard normal function (Navidi, 2006), and σ is the standard deviation. The difference between the two is that the logistic model has a steeper slope near t_{50} than the cumulative normal model. The s-curve models do not contain explicit parameters for geological conditions and the economy, but Q would certainly be influenced by geological conditions and t_{10} and t_{90} by the economy.

To make comparisons easier, the 10% and 90% exhaustion years t_{10} and t_{90} are used to characterize the time responses. For the logistic model, we can write

$$t_{10} = t_{50} + \tau \ln(1/9) \tag{4}$$

and

$$t_{90} = t_{50} + \tau \ln(9) \tag{5}$$

For the cumulative normal model, we have

$$t_{10} = t_{50} + \sigma D(0.1) \tag{6}$$

where D is the inverse cumulative standard normal function, and

$$t_{90} = t_{50} + \sigma D(0.9) \tag{7}$$

The next step is to linearize the exhaustion. The logistic model is linearized through the logit (pronounced *loajit,* from *logistic*) transform, given by

$$\mathit{logit}\,(e_t) = -\ln(1/e_t - 1) \tag{8}$$

and the cumulative normal model is linearized with the probit (pronounced to rhyme with *hobbit*, from *probability*) transform, given by

$$\mathit{probit}\,(e_t) = D(e_t) \tag{9}$$

The purpose in using these transforms is to help stabilize the estimates of long-term production by reducing the sensitivity of the estimate for long-term production to small deviations near t_{50} (Meyer et al., 1999).

The square of the correlation coefficient, r^2, is used as the measure of the quality of the fit. This parameter is commonly used in statistics to indicate how good a linear model is (Navidi, 2006). For each transform, the value of Q is varied to make r^2 as large as possible, with the choice of the logistic or normal model depending on whether the logit or probit transform gives a higher value for r^2. This procedure is attractive because these are simple one-parameter fits. Finding Q takes one second with Excel's equation solver, and repeated fits can be found efficiently with a VBA macro (Rutledge, 2010).

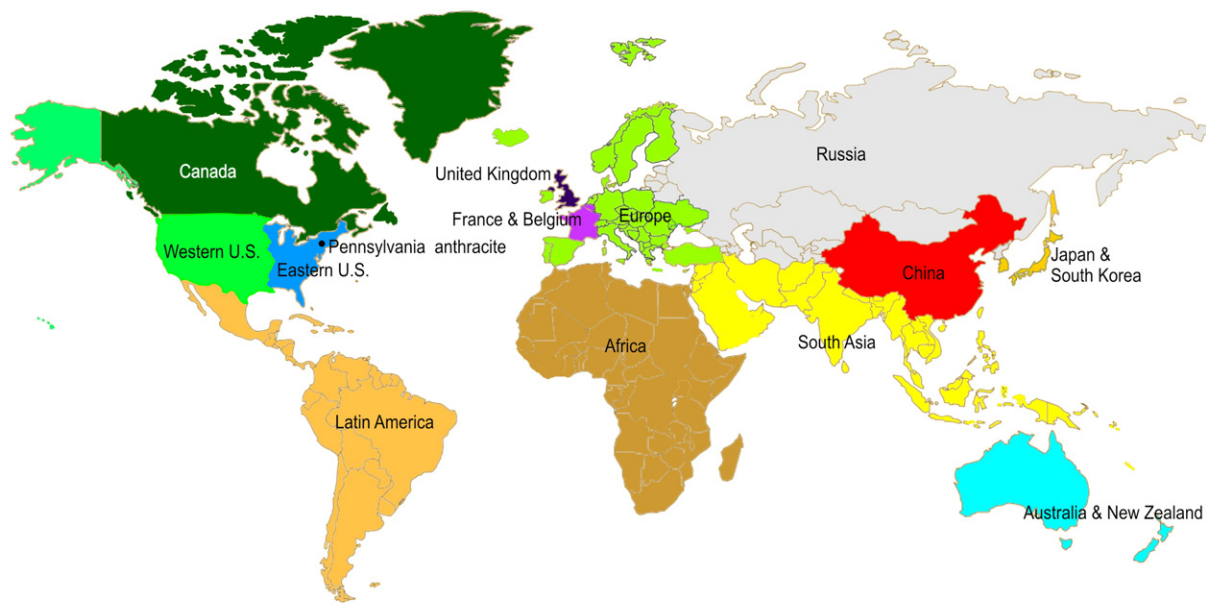

Fig. 2. The fourteen regions of the world for production and reserves analysis. Russia includes all of the former Soviet Union except the Ukraine, as well as Mongolia and North Korea. Europe includes the Ukraine and Turkey, but not the United Kingdom, or France and Belgium, which are treated as separate regions. South Asia also includes the Middle East, southeast Asia, Taiwan, and the islands between Asia and Australia. Latin America includes Mexico. New Zealand is included with Australia. Canada includes Greenland, which has reserves, but no production yet. For the United States, the Mississippi River is the dividing line between East and West. For this analysis, the Eastern United States does not include anthracite production from Pennsylvania, which is treated as a separate region.

After Q has been determined, the other parameters can be found from the y-intercept y and the slope s calculated from the linear regression formulas (Navidi, 2006) as

$$t_{50} = -y/s \tag{10}$$

and

$$\tau = 1/s \tag{11}$$

for the logistic model, and

$$\sigma = 1/s \tag{12}$$

for the cumulative normal model.

There are additional considerations. In the early years, the transformed data drift away from a linear trend. This can be seen in the plots of residuals, which are the differences between the linearized data and the regression line. This means that a first year for the fit must be chosen. In order to prevent the early points from having an unduly large influence, the general rule used was that the starting year for the fit is the first one that gives a residual smaller than the largest of the later residuals. However, for the mature regions, the recent residuals become quite large, and this criterion was not sufficient. For two mature regions, Pennsylvania anthracite, and France and Belgium, there is a sharp slope change in the residuals at the beginning of the Long Depression in 1873, and this year was taken as the starting point for the fit. For Japan and South Korea, the residuals between the two world wars were used for the comparison with the residual for the starting year.

Sometimes the linearized data show a change in slope. This can be interpreted as a change in t_{10} and t_{90}. For example, for South Africa, the boycott period was associated with a speeding up of production. In these cases, r^2 was calculated for both the early and late periods, and a weighted average was used. Sometime there are completely distinct early and late trends with a gap in between. For example, for the Western United States, there are completely different fits for the long-term production estimate before and after the passage of the Clean Air Act Extension in 1970 and the expansion of railroads to the regions. Finally, the curve fits can fail – the fit for long-term production estimate does not always show a maximum in r^2. This is the situation for the developing regions South Asia and Latin America. For these regions, a different estimate for long-term production based on reserves is used.

The approach in this paper is different from Hubbert linearization, first developed for oil and gas estimates by King Hubbert (Hubbert, 1982) and later popularized by Kenneth Deffeyes (Deffeyes, 2001). In Hubbert linearization, the ratio of annual production to cumulative production is plotted on the y-axis and cumulative production is plotted on the x-axis. An x-axis intercept is then extrapolated from the

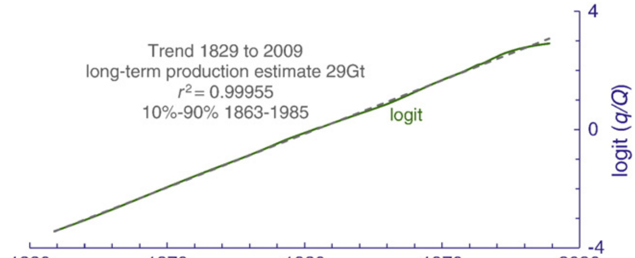

Fig. 3. Linearized British production data with the regression trend line.

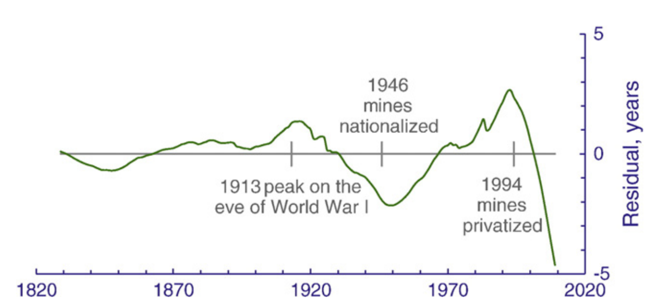

Fig. 4. Residuals for the linearized British data and the regression line in Fig. 3. The residuals have been growing larger in recent years.

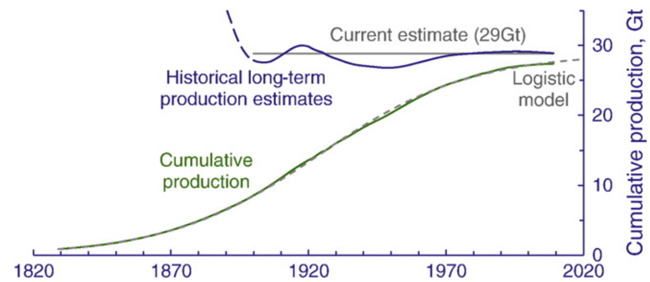

Fig. 5. Historical long-term production estimates for British coal. The cumulative production and the logistic model are shown for comparison.

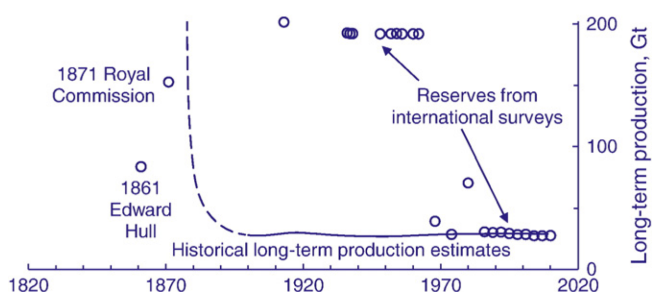

Fig. 6. Comparison between the reserves in the international surveys (WEC, various years) and the historical long-term production estimates for British coal.

data to provide an estimate for the long-term production. The advantage of Hubbert linearization is that it gives an excellent way to visualize the trend and the estimate. Hubbert linearization has primarily been used for oil and gas. Willem Nel and Christopher Cooper have also applied Hubbert linearization directly to world coal production, but these points do not fall very close to a straight line (Nel and Cooper, 2009). More recently Steve Mohr used Hubbert Linearization to analyze national coal production, and then sums to find a world total (Mohr, 2010).

Tadeusz Patzek and Gregory Croft make coal production estimates by fitting directly to the cumulative production (Patzek and Croft, 2010). They criticize Hubbert linearization, writing, "This fit is unstable and often does not intercept zero to yield an estimate of ultimate coal recovery." It has been my experience, also, that curve fits for the long-term production estimate based on Hubbert linearization are usually less stable than those based on cumulative production. One reason for this is that the Hubbert linearization includes annual production as a factor. Estimates based on cumulative production are more stable than those using annual production because there is a smoothing effect when the influence of a particular year's production is spread out over many years. However, estimates based on cumulative production are slower to respond to trends that change in time than a Hubbert linearization. For coal, there is an additional reason to prefer cumulative production fits to a Hubbert linearization. Annual production shows large fluctuations in strike years, and a Hubbert linearization gives these years undue influence. Patzek and Croft use multiple *s*-curves for their fits at the world level. In contrast, in this paper, one *s*-curve is used for each region at any given time, so that only one parameter, the long-term production estimate Q, is fit. This is helpful in characterizing the stability of the long-term production estimates. I have followed Donald Leach's approach of plotting the historical evolution of the estimates in time to characterize the stability (Leach, 1981). There is an additional advantage in using regional fits rather than a global one. Coal markets *are* regional; only about 15% of world coal production is exported (BGR, 2007). All this said, Mohr's estimate for long-term production and the one from Patzek and Croft are similar to the one developed here.

Table 2
Comparison between the calculated and observed t_{10} and t_{90} years. The observed t_{10} and t_{90} years are based on the current estimate for long-term production. The production in the observed 90% exhaustion year is also given. For the United Kingdom, the actual 90% year was 1984. This year and 1985 were strike years with unusually low production. Because of this, I used the 1983 production for the comparison to peak production. The average annual production in the observed t_{90} year is 43% of the peak production.

Region	Regression t_{10}, t_{90}	Observed t_{10}, t_{90}	% of peak production at the observed t_{90}	Peak production Mt	% of long-term production estimate at peak
United Kingdom	1863, 1985	1864, 1984	41	292	41
Pennsylvania anthracite	1881, 1953	1882, 1952	41	90	51
France and Belgium	1877, 1985	1877, 1981	33	88	73
Japan and South Korea	1919, 1989	1918, 1988	56	63	66

For the analysis in this paper, the world is divided into 14 regions, shown in Fig. 2. These regions are selected to give coherent production histories, so they can each be modeled by a single *s*-curve at any one time. We will start with the mature regions, where production has fallen by more than a factor of ten from the peak. There are four of these: the United Kingdom, Pennsylvania anthracite, France and Belgium, and Japan and South Korea. Then we consider the active regions: Australia, China, Africa, Europe, Russia, Western United States, Eastern United States, Canada, South Asia and Latin America.

Comparisons will be made between our estimates for long-term production and the cumulative production plus the reserves given in the international surveys (WEC, various years). These surveys are the *Survey of Energy Resources* of the World Energy Council, the earlier *Statistical Year-book* of the World Power Conference, and the first international survey, *The Coal Resources of the World*, from the 12th International Geological Congress in 1913 (IGC, 1913). The current WEC editors, Alan Clarke and Judy Trinnaman, do an admirable job of managing the surveys. However, surveys have limits. For example, China, by far the world's largest producer of coal, has not responded to the survey requests since 1992, and the WEC surveys have been using the 1992 numbers since then. Also, the criteria used to calculate

Table 1
Comparisons between the range of historical long-term production estimates and reserves for the four mature regions. The first year for calculating the range is 1900, except for Japan and South Korea, where production developed later, and the range calculation begins in 1950. The calculations for Pennsylvania anthracite, France and Belgium, and Japan and South Korea are available on-line (Rutledge, 2010).

Region	Current production Mt	Cumulative production Gt	Long-term production estimate Gt	Long-term production estimate range Gt	Early reserves + cumulative Gt	Reserves year	Long-term production estimate/ (early reserves + cumulative)
United Kingdom	18	27.4	28.9	26.8–30.0 (11%)	153	1871	19%
Pennsylvania anthracite	1.6	5.03	5.05	3.1–5.1 (40%)	12	1921	42%
France and Belgium	0.2	7.2	7.6	4.3–8.5 (55%)	33	1936	23%
Japan and South Korea	3.8	3.6	3.7	2.5–3.9 (36%)	17	1936	21%

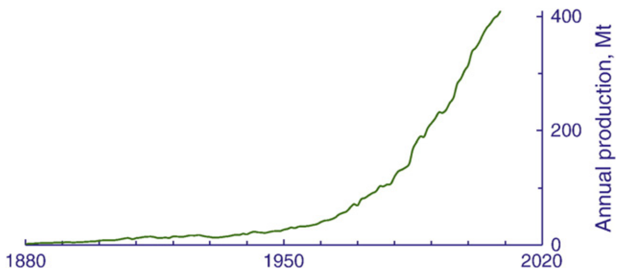

Fig. 7. Annual production for Australia (Davidson et al., 1930 for production before 1900, Mitchell, 1998a, for production from 1900 to 1980, and BP, 2010, for production since then). New Zealand is included.

reserves vary from time to time and from place to place. In many countries, the criteria have become more conservative with time. Finally, the early reserves were calculated on a coal-in-place basis. Beginning with the 1974 survey, the basis was changed to recoverable coal. However, India and Brazil only adopted recoverable coal accounting for the 2007 survey.

3. The United Kingdom

Fig. 3 shows the logit transform of the British production data with 29 Gt as the long-term production estimate. This gave the highest value of r^2, 0.99955. This is the only one of the 14 regions where all of the available annual data are used for the fit. However, this is because annual production data are not available before 1830. The cumulative production through 1829 comes from Sidney Pollard, who estimates the production from 1750 through 1829 as 897 Mt (Pollard, 1980). The production before 1750 is not taken into account in the calculation of cumulative production here. When r^2 is this high it is not easy to see the differences between the data and the model on a graph, and the residuals give a better picture. The residuals are calculated as the differences between the linearized data and the regression line. The plots are easier to interpret if the residuals are expressed in units of time. For this, the points are multiplied by the slope s of the regression line. This allows us to interpret a model as a production schedule. Positive residuals indicate that production is ahead of schedule, and negative residuals show that production is lagging. The residuals are plotted in Fig. 4. There are several slope changes in the residuals that appear to be associated with historical events. For example, there is a downward slope after the First World War. After the mines were nationalized in 1946, the slope turns up. Finally, the slope turns down again before the mines are privatized. The residuals are now five years lagging.

Could the current 29-Gt estimate for long-term production have been made earlier? Fig. 5 shows the historical long-term production estimates. By a historical estimate, I mean that only the data available in that year are used. It is a calculation that someone could have done at the time. In the years before 1900, the historical estimates are unstable, and they go off the top of the graph. However, by 1900, they have settled down, staying within an 11% range since then. The current lagging residuals are pulling the estimate for long-term

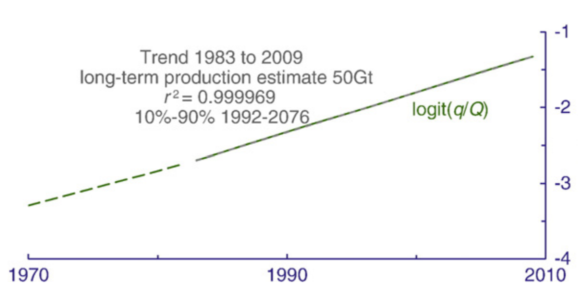

Fig. 8. Linearized production data for Australia and the regression trend line.

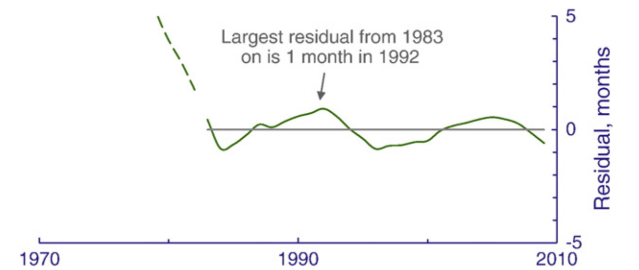

Fig. 9. Residuals for the linearized production data for Australia and the regression line in Fig. 8.

production slowly down toward the cumulative production approaching from below.

How does the accuracy of the historical estimates compare with reserves? Fig. 6 compares the reserves and the historical long-term production estimates. One consideration in making this comparison is that reserves correspond to future production, while the long-term production estimate includes past production. For this reason, the contemporary cumulative production is added to the reserves for the comparison. This is done consistently in the graphs in this paper. Notice that the 1871 Royal Commission, in revising Hull's work, adjusted the estimate of minable coal in the wrong direction. The 1871 Royal Commission's work formed the basis for the reserves until 1968, when there was a collapse. Reserves have the requirement of economic suitability, and the collapse reflects a recognition that the opportunities for new mines were limited. This is consistent with the fact that of the five collieries with producing faces today, the youngest, Kellingley, started production in 1965. However, this awareness came very late in the production cycle – cumulative production by then had reached 83% of the current fit for long-term production estimate.

In the conventional classification, the coal that could potentially be produced economically is divided into *reserves* and *resources*. Reserves are the parts that are well characterized and that could be recovered economically now. The rest are resources. In the literature, it is often assumed that over time, resources will be converted to reserves as needed. For example, Thomas Thielemann, Sandro Schmidt, and Peter Gerling, from the German resources agency BGR, in making projections for future world coal production through 2100, assumed a conversion of 411 Gt of resources to reserves during the next ninety years (Thielemann et al., 2007).

At the level of an individual mine, this approach is justified. Here the term reserves refers to the coal that is characterized in detail by drilling cores and seismic surveys and that is in a detailed production plan. Nearby coal in the same seam that would need additional surveys, infrastructure and planning would be considered resources. However, it is not clear that this picture is appropriate at the national level, because national surveys are not as detailed as those for individual mines. In practice, the conversion can go the other way, from reserves to resources. For example, in the 2001 WEC survey, Germany reported proved, recoverable bituminous reserves as 23 Gt (WEC, 2001). In the following survey in 2004, the bituminous reserves

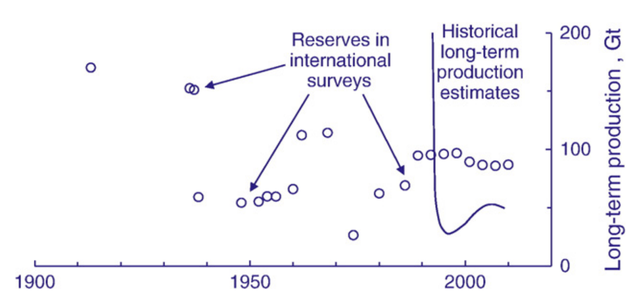

Fig. 10. Comparison between the reserves for Australia and New Zealand (WEC, various years) and the historical long-term production estimates.

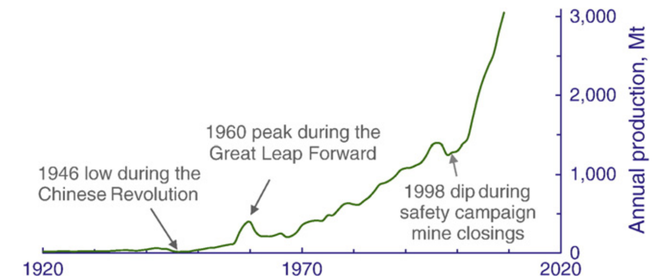

Fig. 11. Annual production for China (Thomson, 2003, for production through 1980, and BP, 2010, for production since then).

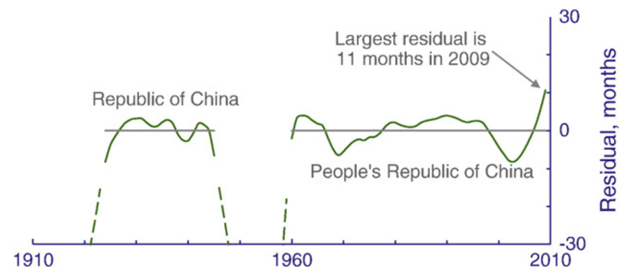

Fig. 13. Residuals for the linearized Chinese data and the regression lines shown in Fig. 12.

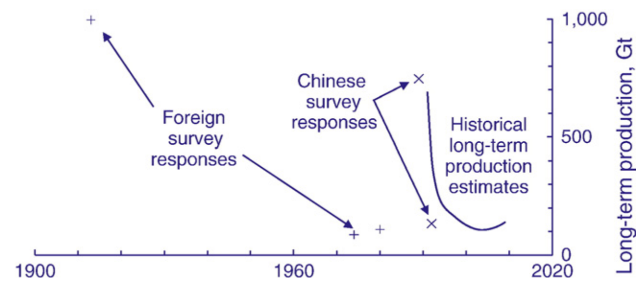

Fig. 14. Comparison between reserves reported in the international surveys (WEC, various years) and the historical long-term production estimates.

had dropped to 183 Mt (WEC, 2004). This astonishing reduction was accompanied by the remarkable explanation, “Earlier assessments of German coal reserves (e.g. end-1996 and end-1999) contained large amounts of speculative resources which are no longer taken into account. Much of the former ‘proved amount in place’ and ‘proved recoverable reserves’ has been moved to ‘additional amount in place’ and ‘additional reserves recoverable,’ respectively. The actual amounts in the surveys are as follows. In 2001, the proved amount in place was 44 Gt, the additional amount in place was listed as 187 Gt, while the additional reserves recoverable entry was blank. In 2004, the proved amount in place was 0.4 Gt, additional amount in place was 23 Gt, and additional reserves recoverable was 8 Gt. Left unexplained is the accounting standard by which “large amounts of speculative” resources were listed as proved, recoverable reserves in the first place.

As another example of the conversion of reserves to resources, in 1913, British reserves were 189 Gt (IGC, 1913). However, for 2008, the BGR listed UK resources as 187 Gt (BGR, 2009) and reserves as 432 Mt.

Are these reclassifications as resources appropriate? It is questionable whether there will be significant production from these fields in the future. In his 1979 classic, *World Coal Reserves*, (Fettweis, 1979) Gunter Fettweis indicated that in the German-speaking world, there was a minerals category that he translated into English as occurrences (*Vorkommen* in German). Fettweis used this word to describe deposits that were not of economic interest. It may be more appropriate to label most of the British coal and the German bituminous coal as occurrences rather than resources.

4. Summary for the mature regions

Table 1 shows comparisons between the historical long-term production estimates and the reserves for the four mature regions. None of the four regions came close to producing their early reserves. On the other hand, it appears that in each case the range for the historical estimates is a good one. The average of the ranges in percentage terms is 36%.

Several investigators have used production curve fits to predict a peak year for world coal production (Hook et al., 2010; Mohr and

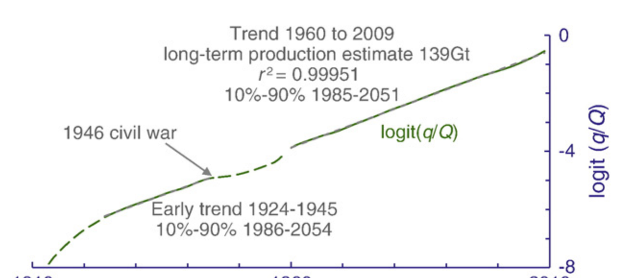

Fig. 12. Linearized Chinese production data, together with early and late regression trend lines.

Evans, 2009; Patzek and Croft, 2010). There are no predictions of peak years in this paper. The reason for this is the historical experience for the mature regions, where the peaks have come in very different parts of the production cycle. Table 2 shows cumulative production in the peak year for the mature regions, expressed as a percentage of the long-term production estimate. These vary from 41% for the United Kingdom to 73% for France and Belgium. This indicates that it would be difficult to predict a peak year correctly for the active regions, and by extension, for world coal. On the other hand, the calculated t_{90} years are close to the observed ones, with an average error of two years.[2]

To summarize the results for the four mature regions, the fitting process gives better estimates of the long-term production than the reserves. In each case, the early reserves were too high – four times too high, on average. The success of the historical long-term production estimates in characterizing the actual production is the justification for our next step. In the following sections, the estimating approach will be applied to the active regions, where we do not know how the production will turn out.

5. Australia

Australia has been the world's largest coal exporter since it passed the United States in 1984 (ABARE, 2008; EIA, 2008). The annual production is shown in Fig. 7. Production reached 414 Mt in 2009, including 5 Mt for New Zealand. The current estimate for long-term production is 50 Gt. The linearized data appear in Fig. 8 and the residuals are shown in Fig. 9. In general, the residuals for the active regions are smaller than for the mature regions, and for this reason, they are plotted in months rather than years. The number of months is calculated by multiplying the residuals in years by twelve. The starting year for the fit is 1983, the first year that the residual is smaller than

[2] The fitted years and the observed years are not exactly comparable, because the fitted values are shown rounded to a whole year, while the observed years indicate that the 90% exhaustion point was reached sometime during the year. There would be more consistency if the fitted years were rounded up, but this would have been confusing in other contexts, so it was not done.

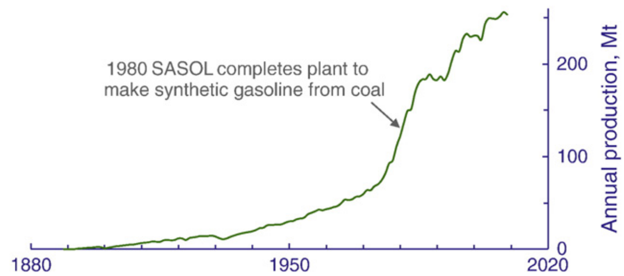

Fig. 15. Annual production for Africa (Mitchell, 1998a, for production through 1980, and BP, 2010, for production since then).

one of the later residuals. Fig. 10 shows the comparison between the historical long-term production estimates and the reserves. The reserves plus cumulative production has varied over the years from a high of 170 Gt in 1913 to 27 Gt in 1974. The value from the 2010 survey is 87 Gt (WEC, 2010. The historical fits appear to be stabilizing, but only recently, starting around 1995. For this reason, the historical fits for long-term world production will start in 1995.

6. China

China succeeded the United States as the world's largest producer of coal in 1985. Chinese production (Fig. 11) has seen astonishing growth in recent years, reaching 3,050 Mt in 2009. China now accounts for 44% of the world's production. Chinese statistics are less reliable than for other regions. One historian, Elspeth Thomson, describes the problems with Chinese statistics in the following terms: "figures deliberately inflated or deflated by low level bureaucrats trying to get some message across to superiors. For example, in order to get bonuses they would report the targets were reached when they weren't, or they would under-report to try to get more funding next year, etc" (Thomson, 2003). Official figures indicate that production tripled during the Great Leap Forward. Thomson comments, "During this period, as a result of wildly exaggerated reports from low level managers, and the fact that so many pits were involved, the planners really did not know just how much coal was being produced."

The linearized data are shown in Fig. 12. The curve begins to sag in 1946, when China descended into civil war, and production fell to 19 Mt. The earlier trend is during the time that the Republic of China (ROC) was the legal government. This part of the trend is not used in the fit for long-term production, but is shown to indicate the continuity with the later trend for the People's Republic of China (PRC). The calculated years for 90% exhaustion for the two trends are close, 2054 for the ROC and 2051 for the PRC. The residuals are shown in Fig. 13. The recent residuals are rather large, and this is causing the estimates for long-term production to rise. This can be seen in Fig. 14, which compares the historical long-term production estimates to reserves. The graph for historical fits has a bowl shape. The appearance is similar to that to Australian coal in 2000 (Fig. 10),

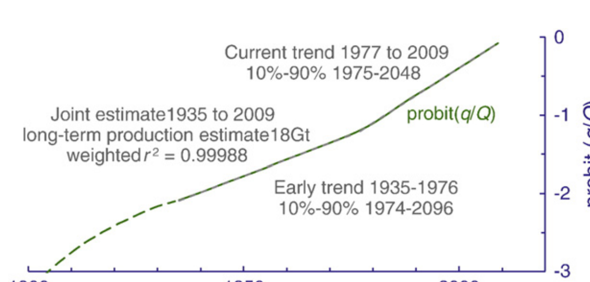

Fig. 16. Linearized African data with early and late regression trend lines.

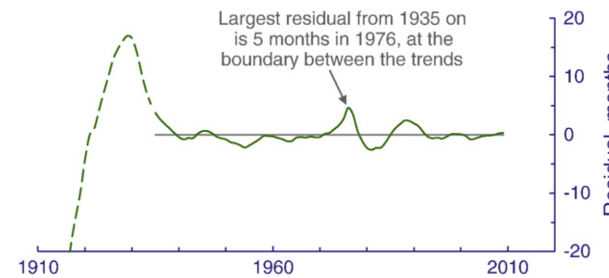

Fig. 17. Residuals for the linearized African data and the regression line segments shown in Fig. 16. The residuals are expressed in time units by multiplying by the slope of the corresponding regression line segment in Fig. 16.

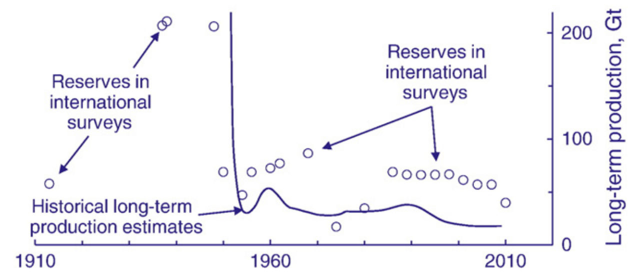

Fig. 18. Comparison of the African reserves (WEC, various years) with the historical long-term production estimates.

when there had been a minimum in the historical fits, but at that time, no maximum. The maximum came later, defining a range for the long-term production estimates. For China, this range-defining maximum has not yet taken place. However, there is no guarantee that that the fits will stabilize soon, and it is possible that in the future, it will be appropriate to retreat to an estimate based on reserves.

The situation with Chinese coal reserves (Fig. 14) is unsatisfactory. The three early responses were done by foreigners(+'s in the figure). The Chinese themselves have only responded twice (×'s in the figure) to the surveys, in 1989 and 1992. Unfortunately, the Chinese responses differ by a factor of six.[3] The World Energy Council has been using the 1992 numbers ever since, without adjusting for the production since then. It is hard to know what to make of this. The current reserves plus cumulative production, 162 Gt (WEC, 2010), is not greatly different from the current long-term production estimate, 139 Gt.

7. Africa

Beginning in the late 70's, African production (Fig. 15) shows an interesting change in slope in the linearized data (Fig. 16, with residuals in Fig. 17). The probit transform is used here because it gave a higher r^2 value than the logit transform. This was during the period of international boycotts of South Africa, when production sped up. Europe and Russia also show a change in slope after the collapse of the Soviet Union. When there is a change in slope, early and late r^2 values were calculated using the same Q. Then an average for r^2 was calculated, weighted by the sum of the squared deviations from the mean for each period. The break-point year between the early and late period was chosen to give the highest weighted r^2. The long-term production estimate that gives the highest weighted r^2 is 18 Gt. The speed up causes a large change in the calculated t_{90}, which moves forward from 2096 to 2048. Fig. 18 shows the comparison between

[3] The German resources agency BGR gives coal reserves for China as 192 Gt (BGR, 2009), based on data provided to the BGR by the Chinese government (Sandro Schmidt, personal communication). This falls between the 1989 and 1992 reserves in the World Energy Council surveys.

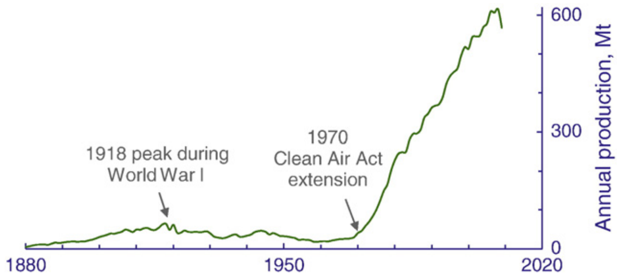

Fig. 19. Annual coal production for the United States west of the Mississippi River (Eavenson, 1942, EIA, various years, Milici, 1997, USBOM, various years, USGS, various years).

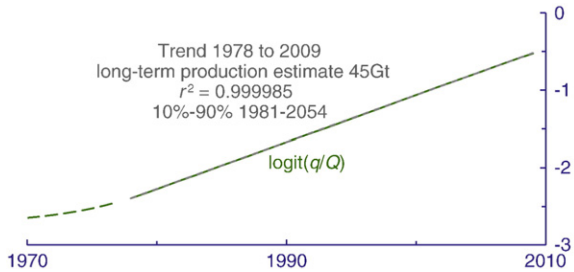

Fig. 21. Linearized late production data for the Western United States and the regression trend line.

reserves and the historical estimates for long-term production. The reserves plus cumulative production has varied from a high of 222 Gt in 1936 to a low 17 Gt in 1974. The 2010 survey value is 40 Gt (WEC, 2010).

8. Western United States

The production history for the Western United States shows two cycles (Fig. 19). The early cycle peaked in 1918 at 65 Mt. At the time, the state of Colorado was the leading producer at 11 Mt, primarily from underground mines. The principal uses of Colorado coal were for locomotives and for smelting. By 1962, western production had fallen to 19 Mt. Then the Clean Air Act Extension was passed during the Nixon Administration, and production took off again. This legislation encouraged the use of low-sulfur coal, which was in limited supply in the east, but abundant in the west. Production in 2009 was 568 Mt, dominated by the Wyoming surface mines, which produced 391 Mt, primarily for electricity generation. The railroad development by the Burlington Northern Railroad, now BNSF, and the Union Pacific Railroad has been just as remarkable as the increase in coal production. The most distant power plants are 3000 km away from the Wyoming mines.

The early linearized data are shown in Fig. 20, and the late data are shown in Fig. 21. The early Q value is 3.0 Gt, while the late one, 45 Gt, is fifteen times larger. Canada and the Eastern United States also show this pattern, with a 4:1 ratio. Fig. 22 shows the residuals. For the current fit, the largest residual is only a month. The historical estimates are shown in Fig. 23, together with the cumulative production, the early cumulative normal model, and the late logistic model. The r^2 value of 0.999985 is the highest of the 14 regions, and the historical fits appear to be stabilizing quickly.

Fig. 24 shows the comparison between the sum of the historical long-term production estimates for the three regions of the United States (Pennsylvania anthracite, Western United States, and Eastern United States) and the reserves reported in the international surveys. The current sum of the historical estimates is 132 Gt, compared with a reserves plus cumulative production of 306 Gt. The United States reserves have fallen dramatically over the years, from 3839 Gt in 1913 to 237 Gt in the 2010 survey (WEC, 2010). This drop was a result of applying more conservative criteria for minimum seam thickness, maximum depth, and maximum distance to a measurement point. This is different from the reserves collapse in the United Kingdom, which was the result of a shift in reserves accounting to include only coal at operating and planned mines.

9. Summary for the active regions

Table 3 summarizes the results for the ten active regions. In each region, the estimate for long-term production is less than the reserves plus cumulative production. In percentage terms, the lowest estimate for long-term production is the Western United States at 28% of reserves plus cumulative production, and the highest is China, at 86%. For South Asia and Latin America, the fitting process for the long-term production estimate did not give a maximum for r^2, even when Q values as high as 10,000 Gt were considered. Both regions have shown steady production growth since 1985, with South Asia at 7% and Latin America at 6%. This exponential growth will not go on forever, but it has gone on long enough to cause the fitting process to fail. In these cases, the reserves plus cumulative production is used as the estimate for long-term production in the calculation of t_{90} . However, it should be recognized that based on the experience of the other twelve regions, the reserves plus cumulative production is likely to be too high as an estimate for long-term production.

10. Long-term production estimates for world coal

Table 3 also gives the world totals, including the four mature regions, and the results are plotted in Fig. 25. The current total for the long-term production estimates is 680 Gt, and this sum has varied over a 14% range since 1995. Many individual regions have a larger range than this, but the estimates for some regions have been rising, like China, and others have been falling, like the United States, and this helps to reduce the range. The estimate for long-term production is lower than the current reserves plus cumulative production, 1163 Gt (WEC, 2010). For other comparisons, Steve Mohr's Hubbert linearization based on individual countries gave 702 Gt (Mohr, 2010), and Tadeusz Patzek and Gregory Croft's global multi-cycle Hubbert analysis gave 630 Gt (Patzek and Croft, 2010).

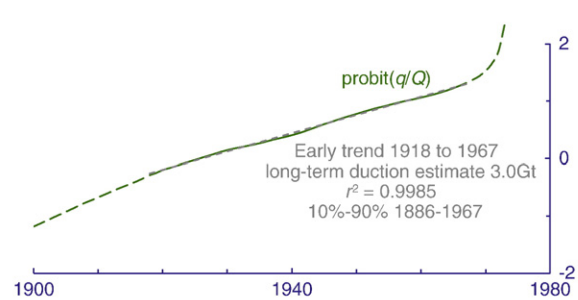

Fig. 20. Linearized early production data for the Western United States and the regression trend line.

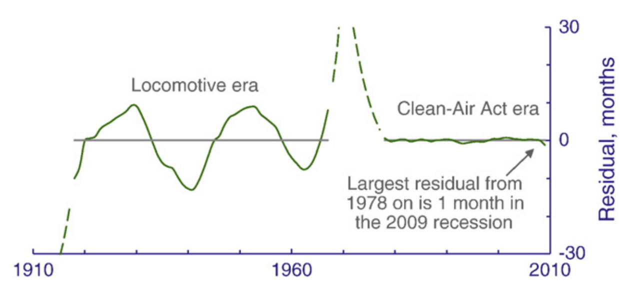

Fig. 22. Residuals for the linearized data for the Western United States and the early and late regression lines.

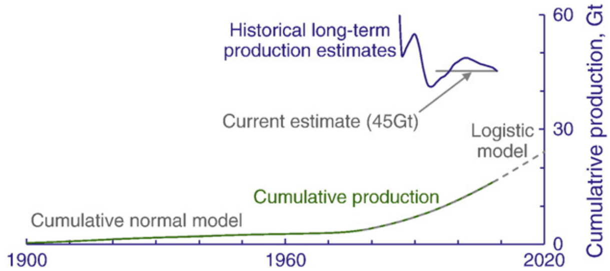

Fig. 23. Historical long-term production estimates for the Western United States. The cumulative production and early and late models are shown for comparison.

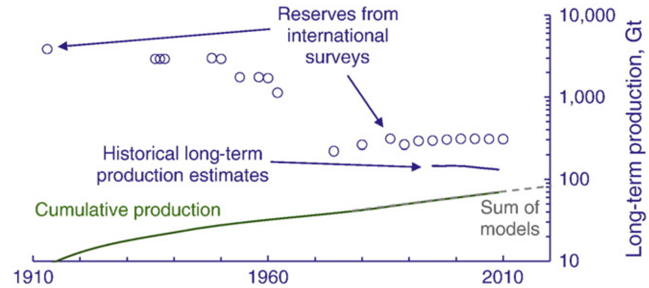

Fig. 24. Historical long-term production estimates for United States coal production, compared with the reserves reported in the international surveys (WEC, various years).

A fundamental limitation of making estimates from production histories is that undeveloped regions are not taken into account. For example, there is a large coal field on the North Slope of Alaska with no transportation facilities (Flores et al., 2003). This coal does not show up in the production curve fits, and the existing geological surveys are not detailed enough for it to count as reserves either. However, the long debate over drilling for oil on the Arctic National Wildlife Refuge, makes it questionable whether the North Slope coal field will be developed in this century, because of environmental concerns. Coal mines and coal trains would be extremely destructive to the arctic plants and wildlife. Russia also has large coal fields in central Siberia, the Tungus and the Lena, with no railroad access (Melnikov, 1972). As with the North Slope coal field in Alaska, the Tungus and Lena fields do not figure in Russian coal reserves. There is extensive coal mining in Siberia, but it takes place in the Kuznetsk and Kansk-Achinsk fields to the south, near the Trans-Siberian railroad. Russia will likely exhaust the Kuznetsk and Kansk-Achinsk fields before developing the Tungus and Lena fields. Even without production from the Tungus and Lena fields, the calculated year for 90% exhaustion for Russia is 2101. There may not be significant production from the Tungus and Lena fields until the next century.

11. Year of 90% exhaustion for world coal

The calculated year of 90% exhaustion, 2070, gives a time frame for thinking about alternatives, particularly in electricity production, where coal dominates. For comparison, Steve Mohr's national Hubbert Linearization gave 2081. Mohr also developed a supply–demand analysis for a "best guess" case of 961 Gt (close to reserves + cumulative) that gave 2095 (Steve Mohr, personal communication). The result for Patzek and Croft's multi-Hubbert cycle analysis was 2058 (Patzek and Croft, 2010).

The calculated 90% exhaustion year 2070 should be considered as a current trend rather than a projection, because there are several regions where there have historically been significant shifts in the production rates, and similar shifts could happen again in the future. South Africa construction of synthetic gasoline plants was accompanied by a shift for t_{90} from 2096 to 2048. A t_{90} of 2070 does not mean that the entire electricity production of coal would need to be replaced by alternatives by 2070. Recall that the annual production in the mature regions at 90% exhaustion was about 40% of the peak value (Table 2). For planning purposes, it would be appropriate to consider replacing 60% of the electricity currently produced by coal with alternatives by 2070, or to compensate by conservation. Hydroelectric generation and nuclear power already contribute 30% of world electricity production (BP, 2010). Wind power has grown at 28% per year for the last decade (BP, 2010), and solar photovoltaic power at 37% per year (BP, 2010), so it is plausible that by 2070, these will make contributions comparable to hydroelectric and nuclear today. Concentrating solar thermal power is at an earlier stage than wind power and solar photovoltaic power, but it could also make a substantial contribution by 2070.

12. Coal in the UN IPCC scenarios

Both the estimates for long-term production in this paper and the WEC reserves plus cumulative production are completely different from what the UN's Intergovernmental Panel on Climate Change (IPCC) assumes is available for production in its scenarios. The maximum cumulative production through 2100 is 3500 Gt for the IPCC's A1C AIM scenario (Volkers, 2000). This is five times the estimate for long-term production given here. In addition, production is still rising in this scenario in 2100, so the eventual implied production would be even larger.

Table 3
Comparisons between the historical long-term production estimates and reserves for the active regions and the world (WEC, various years, EIA, 2009). The numbers for the Eastern United States are without Pennsylvania anthracite. The ranges for the historical estimates are for the years 1995 through 2009. The calculations for Europe, Russia, Eastern United States, Canada, South Asia, and Latin America are available on line (Rutledge, 2010).

Region	Current production Mt	Cumulative production Gt	Long-term production estimate Gt	Reserves + cumulative Gt	Long-term production estimate/ (reserves + cumulative)	Long-term production estimate range Gt	Regression t_{90}
Australia	414	10	50	87	57%	28–53 (51%)	2076
China	3,050	51	139	162	86%	107–201 (68%)	2051
Africa	253	8	18	40	45%	18–27 (49%)	2048
Europe	731	83	134	193	70%	134.1–134.4 (0.2%)	2078
Russia	445	28	65	225	29%	40–65 (40%)	2101
Western United States	568	17	45	160	28%	42–49 (14%)	2054
Eastern United States	404	48	82	137	60%	82–99 (21%)	2084
Canada	63	3	4	10	45%	4–5 (22%)	2030
South Asia	895	15		86		78–113 (40%)	2072
Latin America	94	2		22		12–24 (53%)	2088
World coal (with mature regions)	6941	309	680	1163	58%	653–749 (14%)	2070

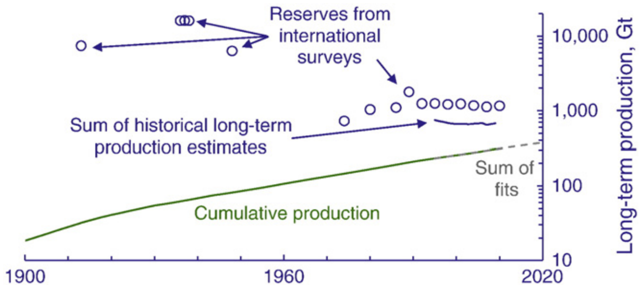

Fig. 25. Comparing the sum of the historical estimates for long-term production with world coal reserves plus cumulative production.

Where does the IPCC get its coal? The IPCC's Special Report on Emission Scenarios says,

> "…about 22.9 ZJ [1 ZJ (zeta joule) = 10^{21} joules] are classified as recoverable reserves (WEC, 1995a; 1998) [the World Energy Council Surveys for 1995 and 1998], over 200 times current production levels. The question is the extent to which additional resources can be upgraded to reserves. WEC (1995a; 1998) estimates additional recoverable reserves at about 80 ZJ, although it is not clear under what conditions these reserves would become economically attractive." (Nakicenovic et al., 2000).

Table 4 shows the reserves categories for the World Energy Council surveys. "Recoverable reserves" in the quote above corresponds to the World Energy Council's "proved recoverable reserves." This is the category that is used in the rest of this paper for reserves. I do not use the "additional recoverable reserves" category, but the IPCC does use it. In fact, the implied production for the A1C AIM scenario is more than enough to exhaust it. However, there are problems with the additional recoverable reserves category. One is that many countries ignore it. For example, in the 1998 survey, South Africa, Canada, the United States, India, Japan, China, Germany, and the UK did not respond. Of the total additional recoverable reserves, 91% came from Russia. Another problem with the additional recoverable reserves category is that it is used as a temporary dumping ground when the proved recoverable reserves are reduced, so it is not clear how this would contribute to future production. For example, this is where part of Germany's bituminous reserves ended up in 2004.

The IPCC scenario report references both the 1995 and the 1998 WEC surveys. The proved, recoverable reserves for each year are similar, but the additional recoverable reserves in the 1998 survey are five times higher. This is a clear indication that something is wrong with the category, and that neither number should be used. However, IPCC did use the category, and it chose to use the higher number. To do this, the IPCC had to add the contributions from the individual countries themselves, right past this explicit warning from the World Energy Council, repeated on each page, "The data on resources [the categories in addition to proved recoverable reserves, including additional recoverable reserves] are those reported by WEC Member Committees in 1997. Thus they constitute a sample, reflecting the information available in particular countries: they should not be considered as complete, or necessarily representative of the situation in each region. For this reason, regional and global aggregates have not been computed" (WEC, 1998). The WEC gave compelling reasons for not summing the category, but the IPCC did it anyway.

Since 1998, the additional recoverable reserves have collapsed, and in 2007, they were one-twentieth as large as they were in 1998. Russia, dominant in 1998, ignored the category in 2007. India, which did not respond in 1998, provided 54% of the 2007 total. India had downgraded its proved recoverable reserves from 92 Gt in 2004 to 56 Gt in 2007, and in the process, 97 Gt showed up as additional recoverable reserves where there were none before.

Table 4
Reserves in the World Energy Council Surveys (WEC, various years). The light blue stripes indicate the 1995 and 1998 surveys that the IPCC referenced for the coal resources in its scenarios, and the pink column shows the collapse of the additional recoverable reserves category. The World Energy Council explicitly declines to sum the additional recoverable reserves, stating that they are neither "complete" nor "representative." I give the sums here only to show the trend for comparison with the IPCC numbers.

WEC survey	Proved recoverable reserves, Gt	Additional recoverable reserves, Gt
1992	1,039	702
1995	1,032	680
1998	984	3,368
2001	984	409
2004	909	449
2007	847	180

13. Conclusions

The estimate for long-term world production is 680 Gt, compared with the reserves plus cumulative production, 1163 Gt. The historical estimates for long-term production from 1995 to present stay within a 14% range. The calculated year of 90% exhaustion is 2070. This gives a time frame for the development of alternatives. This work does not support the use of multiples of coal reserves in the IPCC scenarios.

Both the curve fits developed here and the reserves have strengths and weaknesses. Neither the estimates nor the reserves take into account the development of regions without detailed surveys and transportation access, like the North Slope coal fields in Alaska and the Tungus and Lena coal field in Siberia. Reserves are available early in the production cycle, before the long-term production estimates stabilize. However, the experience of the mature regions is that the reserves are likely to be too high, and the overestimates are not corrected until very late. On the other hand, the historical long-term production estimates have given appropriate ranges for each of the mature regions.

Acknowledgements

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References

ABARE (Australian Bureau of Agricultural and Resource Economics), 2008. Australian Commodity Statistics 2008. Table 244, Summary of Australian statistics for black coal, gives export statistics. Available at http://www.abare.gov.au/interactive/08acs_dec/Accessed October 2010.

Ashworth, W., 1986. The history of the British coal industry, Vol. 5, 1946–1982, the nationalized industry. Oxford University Press, New York, p. 80.

BGR, 2009. Reserves, Resources and Availability of Energy Resources, status: 31.12.2008. Hannover. At http://www.bgr.bund.de/cln_006/nn_322882/EN/Home/homepage__node.html?__nnn=true Accessed October, 2010.

BGR (German Federal Institute for Geosciences and Natural Resources, 2007. Reserves, Resources, and Availability of Energy 2005. Hannover. In 2004, 755 million tons of hard coal was traded, being 685 million tons seaborne and 70 million tons within the transnational overland trade, p. 25. At http://www.bgr.bund.de/cln_006/nn_322882/EN/Home/homepage__node.html?__nnn=true Accessed October, 2010.

BP, 2010. BP Statistical Review of World Energy, available at http://www.bp.com Accessed June, 2010.

Church, R., 1986. The History of the British Coal Industry, Vol. 3, 1830-1913, Victorian Preeminence. Oxford University Press, New York. Figure 1.2.

Davidson, C.G.W., Gepp, H., Ward, L.K., 1930. “Report of the Royal Commission appointed to Inquire into and report upon the coal industry,” NSW Parliament. Legislative Assembly. Alfred James Kent, Government Printer.

DECC (Department of Energy and Climate Change of the United Kingdom), 2010. Energy Trends, March, 2010. Table 2.1.

Deffeyes, K., 2001. Hubbert's Peak, the Impeding World Oil Shortage. Princeton University Press. Chapter 8.

Eavenson, H., 1942. The First Century and a Quarter of American Coal Industry. privately published Waverly Press, Baltimore, MD, pp. 426–434. Production Table 20.

EIA, 2008. Annual Energy Review 2008. Table 7.4 Coal Exports by country of destination. Available at http://www.eia.doe.gov/emeu/aer/coal.html. Accessed October 2010.

EIA, 2009. Annual Coal Report 2008," This table allows a calculation of the separate reserves for Pennsylvania anthracite, Western United States, and Eastern United States. The total for the US matches the 2010 WEC survey.

EIA, various years, *Annual Energy Review*, Table 7.2, Coal Production, for production from 1949 to present, available at http://www.eia.doe.gov/emeu/aer/contents.html. Accessed October 2010.

Fettweis, G., 1979. World Coal Resources. Elsevier Scientific Publishing Company, New York, p. 26.

Flores, R., Stricker, G., Kinney, S., 2003. “Alaska Coal Resources and Coal bed Methane Potential, US Geological Survey Bulletin 2198.” The authors give the resources for the North Slope field as 3,900 Gt. Available at http://pubs.usgs.gov/bul/b2198/B2198-508.pdf Accessed October 2010.

Hook, M., Zittel, W., Schindler, J., and Aleklett, K., 2010. Global coal production models based on a logistic model. Fuel 89, 3546–3558.

Hubbert, K., 1982. Techniques of prediction as applied to the production of oil and gas,” Presented to a symposium of the US Department of Commerce, Washington, D.C., June 18–20, 1980. In: Gass, Saul I. (Ed.), Oil and Gas Supply Modeling. : National Bureau of Standards special publication, 631. National Bureau of Standards, Washington, pp. 57–58.

Hull, E., 1861. The Coal-Fields of Great Britain2nd Edition. Edward Stanton, London. The quote from the preface also appears in the first edition, but the coal estimates for Scotland are incomplete in that edition. Hull used the long ton, equivalent to 1.016 metric tons.

IGC (12th International Geological Congress), 1913. In: McInnes, William, Dowling, D.B., Leach, W.W. (Eds.), The Coal Resources of the World, Vol. 1-3. Morang and Company, Toronto. This was the first international survey, but it was not included in the World Energy Council numbering scheme. The IGC survey used the same 1-foot seam and 4,000 foot depth criteria that the 1871 Royal Commission did, although no recovery factor was taken into account in the IGC survey. The results were tabulated as “actual and probable reserves.”

Leach, D., 1981. Re-evaluation of the logistic curve for human populations. Journal of the Royal Statistical Society, Series A (General) 144, 94–103.

Melnikov, N.V., 1972. Canadian Institute of Mining, Metallurgy, and Petroleum (CIM) Bulletin for June. The Role of Coal in the Energy Fuel Resources of the USSR, pp. 77–82. Melnikov gives the resources of the Tungus field as 1,744.8 Gt and the Lena field as 2,647.2 Gt.

Meyer, P., Yung, J., Ausubel, J., 1999. A primer on logistic growth and substitution: the mathematics of loglet lab software. Technological Forecasting and Social Change 61, 247–271 In Section 5, the authors mention the sensitivity of the estimates to small deviations in the middle of the cycle. They suggest using the Fisher-Pry transform to reduce this sensitivity. In practice, the Fisher-Pry transform is commonly plotted on a base-10 logarithm scale, and these plots are equivalent to a logit transform with a scale change.

Milici, R., 1997. Of the US Geological Survey, coal production data for selected states, used for years before 1949. Available at http://pubs.usgs.gov/of/1997/of97-447. The western states included are Arizona, Colorado, Louisiana, Montana, New Mexico, North Dakota, South Dakota, Texas, Utah, and Wyoming. The eastern states included are Alabama, Georgia, Illinois, Indiana, Kentucky, Maryland, Mississippi, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. The western states omitted are Alaska, Arkansas, California, Idaho, Iowa, Kansas, Missouri, Oklahoma, Oregon, and Washington. The eastern states omitted are Michigan, North Carolina, Rhode Island and Massachusetts. Accessed October 2010.

Mitchell, B., 1998a. International Historical Statistics: Africa, Asia, and Oceania, 1750-1993. Macmillan Reference Ltd, London, pp. 1750–1993. Table D2.

Mitchell, B., 1998b. International Historical Statistics, Europe 1750–1993. Macmillan Reference Ltd, London, pp. 1750–1993. Table D2.

Mohr, S., 2010, *Projection of World Fossil Fuel Production with Supply and Demand Interactions*, PhD thesis, the University of Newcastle, Australia.

Mohr, S.H., Evans, G.H., 2009. Forecasting coal production until 2100. Fuel 88, 2059–2067.

Nakicenovic, N., et al., 2000. Special Report on Emissions Scenarios. Section 3.4.3.1, available at http://grida.no/climate/ipcc/emission. Accessed October 2010.

Navidi, W., 2006. Statistics for Engineers, 2nd edition. McGraw-Hill, New York.

Nel, W., Cooper, C., 2009. Implications of fossil fuel constraints on economic growth and global warming. Energy Policy 37, 166–180 Figure 12.

O'Donoghue, J., Goulding, L., Allen, G., 2004. Consumer price inflation since 1750. Economic Trends 38–46 March.

Patzek, T., Croft, G., 2010. A global coal production forecast with multi-Hubbert cycle analysis. Energy 35, 3109–3122.

Pollard, S., 1980. A new estimate of British coal production, 1750–1850. Economic History Review 33, 212–235.

Royal Commission, 1871. Report of the Commissioners appointed to inquire into the several matters relating to Coal in the United Kingdom, Vol. 1. the Royal Stationery Office, Her Majesty's Stationery Office, London, p. xii.

Rutledge, D., 2010. Coal Geology on-line material.xlsm. Excel workbook at http://rutledge.caltech.edu. Accessed October, 2010.

Supple, B., 1987. The history of the British coal industry. 1913-1946 The Political Economy of Decline, vol. 4. Oxford University Press, p. 48.

Thielemann, T., Schmidt, S., Gerling, J.P., 2007. Lignite and hard coal: energy suppliers for world needs until the year 2100 – an outlook. International Journal of Coal Geology 72, 1–14.

Thomson, E., 2003. The Chinese Coal Industry, An Economic History. RoutledgeCurzon.

UK Coal, 2010. Annual Report and Accounts 2009. Available at http://www.ukcoal.com.

USBOM (US Bureau of Mines), various years, *Minerals Yearbooks*, United States Government Printing Office in Washington, DC.

USGS (United States Geological Survey), various years, *Mineral Resources of the United States*. The 1927 edition was published by the US Bureau of Mines. United States Government Printing Office in Washington, DC.

Volkers, C., 2000, Appendix SRES Version 1.1, an Excel workbook with a spreadsheet for each scenario. It includes GDP, population, fossil-fuel production, CO_2 emissions, land use, other greenhouse gas emissions, and carbon sequestration, on a world and regional basis at 10-year intervals. At http://www.grida.no/climate/ipcc/emission/data/allscen.xls Accessed October, 2010 To calculate cumulative production, I used the actual production through 2009, and the scenario production from then on. The IPCC uses energy units, and I converted at the world production average in the *BP Statistical Review 2010* of 21 GJ/t.

WEC, 1998. Survey of Energy Resources. Published by the World Energy Council, London.

WEC, 2001. Survey of Energy Resources. Published by the World Energy Council, London.

WEC, 2004. Survey of Energy Resources. Published by the World Energy Council, London.

WEC, 2010. Survey of Energy Resources. Published by the World Energy Council, London.

WEC, various years, *Survey of Energy Resources*, the World Energy Council, London. The World Energy Council survey now appears every three years, the most recent being the 22nd survey in 2010. Frederick Brown was responsible for *Statistical Year-Books* 1 through 9. These were published under the auspices of the World Power Conference in London. The results were given as "probable total reserves." Under the next editor, Albert Parker, the survey acquired its present name, *Survey of Energy Resources*, with results listed as "total reserves." For the 12th survey in 1974, the reserves criteria became more restrictive, and were given as "known economically recoverable reserves." The 13th survey in 1980 introduced the current category of "proved recoverable reserves."