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Global coal production outlooks based on a logistic model

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Abstract

A small number of nations control the vast majority of the world's coal reserves. The geologically available amounts of coal are vast, but geological availability is not enough to ensure future production since economics and restrictions also play an important role. Historical trends in reserve and resource assessments can provide some insight about future coal supply and provide reasonable limits for modelling. This study uses a logistic model to create long-term outlooks for global coal production. A global peak in coal production can be expected between 2020 and 2050, depending on estimates of recoverable volumes. This is also compared with other forecasts. The overall conclusion is that the global coal production could reach a maximum level much sooner than most observers expect.

Key words:

Future coal production, peak coal, logistic model, historical reserve and resource assessments

1 Introduction

There are generally two different points of view on coal in global energy systems. The first considers how polluting, dirty, and dangerous coal is compared to other energy sources and that coal should be avoided. However, economies are not avoiding coal. It is one of the world's most important primary sources of energy and will remain so for foreseeable time. The other view is the optimistic opinion that there are hundreds of years of coal available for energy production and that declining oil and gas reserves can be compensated for by increased usage of coal. This view is more problematic as it seldom focuses on the really important issue: how much coal is realistically available and how much might be produced in the future?

Coal is presently an important energy source with its 26.5% share of world primary energy [1]. However, society simply demands energy and the services energy makes possible, not necessarily energy from a specific fuel such as coal. This means that if the desired energy can be obtained less expensively and more sensibly from other energy sources, potentially nuclear power or wind, those will be favoured. It follows that it is only recoverable coal that matters, i.e. coal that can be economically delivered to consumers. The depletion of "*easy coal*" can be seen as similar to the end of "*abundant and cheap oil*," as discussed by Campbell and Laherrere [2].

The geologically available amounts of coal are vast, but geological availability is not enough to ensure future production since economics and production restrictions also play an important role. For example, consider the Gillete coal field in Wyoming and the comprehensive investigation of its coal supply by the United States Geological Survey (USGS)'. Luppens et al. [3] assessed the Gillette coalfield and its eleven coal beds and estimated the original coal in place to be 182 Gt with no restrictions applied. Available coal resources, which are part of the original resource that is accessible for potential mine development after subtracting all restrictions, are about 148 Gt. Recoverable coal, which is the portion of available coal remaining after subtracting mining and processing losses, was determined for a stripping ratio of 10:1 or less and resulted in a total of 70 Gt. Applying current economic constraints and using a discounted cash flow at 8% rate of return, the coal reserve estimate for the Gillette coalfield is only 9.1 Gt. While economic conditions definitely have the largest impact, reductions caused by technical and availability restrictions are also significant.

Other studies have found that less than one-half of the total available coal resources examined were available for mining due to restrictions and only one-tenth were considered economically recoverable [4]. This provides some perspective on the influence that restrictions, economics, and coal quality issues can have on available coal supply for future production. In essence, coal-in-place estimates are generally very poor indicators of the amount that actually can be extracted and used by society. Consequently, it is important to study how recoverability and availability has changed over time and attempt to estimate how it may behave in the future. Unless these factors are properly incorporated into projections, any effort to provide future production estimates rest on loose foundations.

For example, increased concern about CO_2 emissions from coal is dramatically changing the economic competitiveness of coal due to CO_2-taxes and the projected cost increases of carbon-capture and storage (CCS). A closer discussion of this is beyond the scope of this study, but has been performed by others [5-8].

1.1 Global distribution of coal

Like all fossil fuels, global coal reserves are very unevenly distributed. A small number of nations control the vast majority of the world's coal reserves. The USA, the former Soviet Union (whose coal deposits have gone to the Russian Federation, Ukraine and Kazakhstan after 1998), China, India, Australia and South Africa together control over 93% of the world's hard coal reserves [9]. They also control around 90% of the world's hard coal resources, along with a majority of the world's brown coal, both reserves and resources [9, 10].

Replacing former Soviet Union with Russia, a group of six nations that control around 82% of the world's coal is created. This group will be called the *Big Six* and is the main focus of this investigation along with some of the most important exporters. Presently the Big Six account for nearly 80% of the world's coal production, with 43% from China alone [9].

The USA, sometimes described as the Saudi-Arabia of coal, has almost 30% of the world's total coal reserves [9]. Russia, with around 20%, has the second largest coal reserves [9]. China and India have 14% and 7% respectively of the world's coal [9] and are of particular interest because they have rapidly growing economies that need more energy. Finally, Australia and South Africa have 9% and 4% respectively of the world's coal reserves [9], and are both significant exporters. South Africa also has a significant coal-to-liquids industry and its coal consumption has been discussed in more detail [12].

The largest coal exporting nations outside the Big Six are Canada, Colombia, Indonesia, Poland, Vietnam and Kazakhstan, combined they account for almost 40% of the world coal exports [10]. They also account for 10% of world coal production [9]. These countries are included in a group called the major exporters. The dominance of the Big Six and the major exporters can be seen in Figure 1.

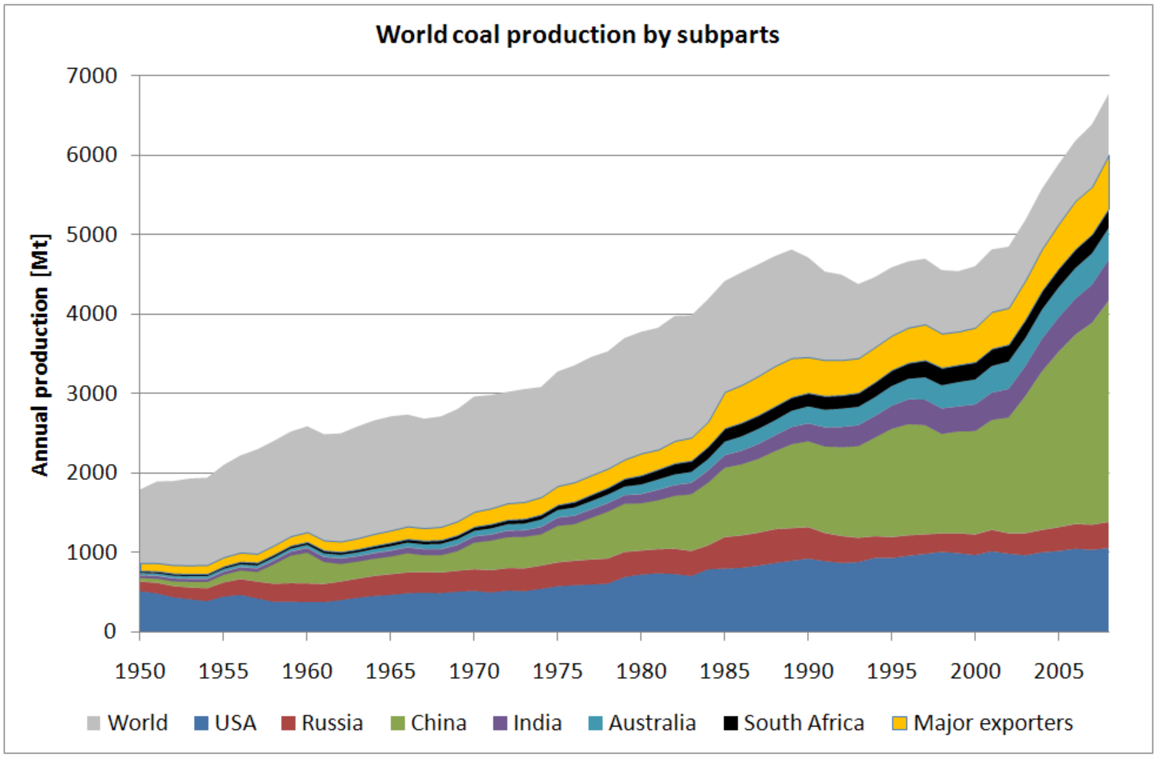

Figure 1: *Total world production 1950-2008 and the contribution from the members of the Big Six and the major exporters. Prior to 1985, the coal production from the Donetsk basin is not included in Russia. In 2008, these countries together accounted for nearly 90% of the total world coal production. The shape of the future global coal production curve in the near and medium term will chiefly be determined by these countries. Data source: [9], [11]*

1.2 The concept of peak coal

Just like other fossil fuels, coal is created over millions of years as the result of the accumulation and transformation of organic debris in a specialised environment of deposition [13]. The slow creation cannot match the extraction rate. If a resource is consumed faster than it is replenished it will unmistakably be subject to depletion. Consequently, coal is a finite resource. From this premise, one may define the term *peak coal* as the maximum rate of the production of coal in any area under consideration, recognizing that it is a finite natural resource and subject to depletion. This is similar to the concept of peak oil and the depletion of coal is as realistic as the depletion of oil. The main differences lie in the amount of available reserves and the actual extraction methods.

Bardi and Lavacchi [14] have explained the peak phenomenon on the basis of a simple theory based on the renowned Lotka-Volterra biological model. The basis of the theory is that, initially, the extraction of an abundant and cheap resource leads to economic growth and to increasing investments in further extraction. Gradually, the cheap and easy resources are depleted and extraction costs become higher because of the need to extract lower quality deposits. In time, investments cannot keep pace with these rising costs; the growth slows down and, eventually, production starts declining. Here, "*costs*" are to be understood in monetary terms as well as energy costs, which grow for physical reasons related to the lower concentration and/or lower quality of the resource. In other words, what creates the bell curve for an energy resource like oil is the variation with time of the net energy of extraction, also known as *Energy Return on Energy Investment* (EROEI). Other works have shown a typical peaking or bell-shaped behavior for production of various natural resources [15, 16].

Similar to oil, coal extraction will get more expensive and complicated to produce as the best and most attractive coal deposits are depleted, finally entering a depletion-driven decline [17]. In addition, better extraction technologies have been found to be largely obscured by decreasing reserve levels as the coal becomes increasingly complicated to mine, effectively meaning that depletion has been able to offset many of the gains from new technology [18, 19]. This is in line with the explanations provided by Bardi and Lavacchi [14].

Empirical data show that some regions have already passed *peak coal*. The United Kingdom peaked in coal production in the 1920s and the downward trend became obvious and unstoppable in the 1930s. Jevons [20] foresaw this event in his 1856 work *The Coal Question* using growth rate extrapolation and an estimate of U.K. coal supply. Some other countries that also have passed peak coal are Germany and Japan (Figure 2). About 20 countries have already passed peak production and the combined production volume declined since 1980 by almost 50 % from 1.200 Mt to 620 Mt in 2006 [21].

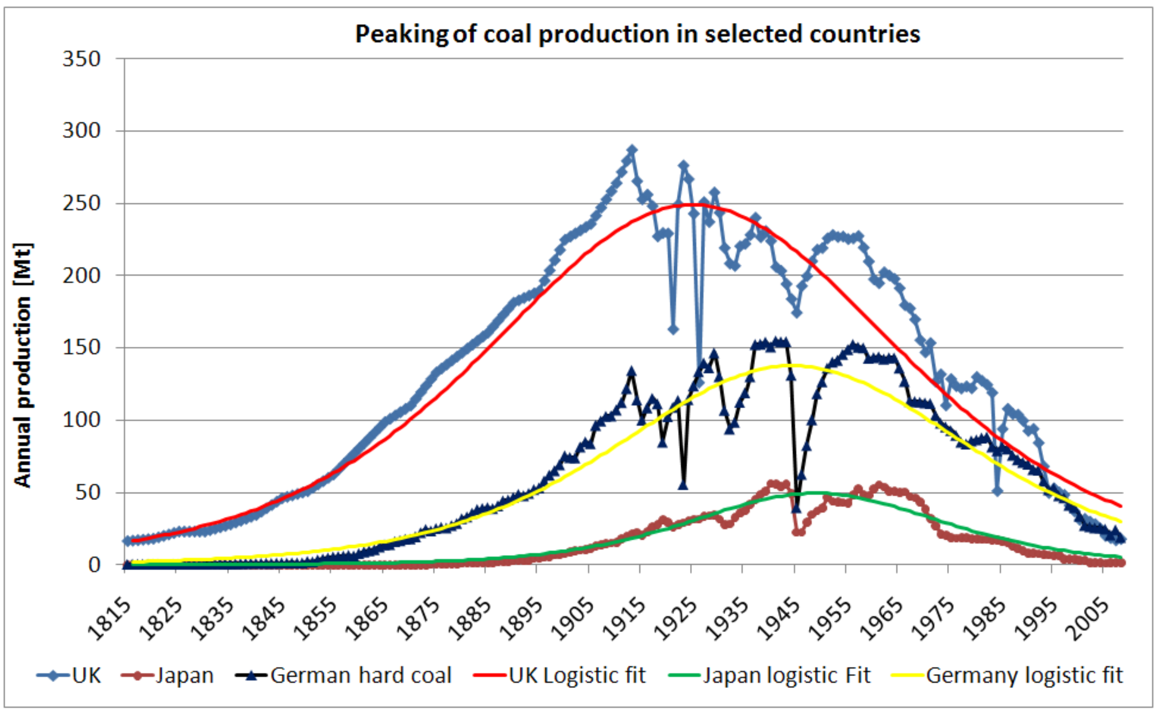

Figure 2: *Coal production of Germany, Japan and the UK 1815-2008. The historical production peaks and clearly shows logistic behaviour. The two world wars, the world depression and some major strikes are visible as dips in the production curves.*

2 Methodology

Historical reserve and resource assessments were gathered from World Energy Council (WEC) and the German Federal Institute for Geosciences and Natural Resources (BGR). Additional data have been taken from official databases compiled by organizations including such as the United States Geological Survey (USGS), the Energy Information Administration (EIA), the BP Statistical Review of World Energy (BP), the International Energy Agency (IEA) and similar sources. Regarding production, the compilation of comprehensive historical production data sets by Rutledge [11] has been used for many countries. From 1981 to 2008 production data from BP [9] have been applied.

The Big Six will greatly influence the global coal production because of their large coal supply and production volumes. The peaking of the Big Six will essentially determine the peak in global coal production. Therefore, the Big Six is an important parameter for projecting future global coal production. Some of the Big Six have a long history of coal production and will decline sooner than other members. For example, the longevity of the American coal supply has been questioned [22, 23, 32]. Other members of the Big Six, such as Australia, have a comparably young coal industry and are only in the beginning of their production curves.

A model for extrapolation of production curves of finite resources was proposed by Hubbert [24, 25]. This approach assumes that production begins at zero, before the production has started, and ends at zero, when the resource has been exhausted. In between, the production curve passes through one or several maxima. Although the actual shape of the production curve may vary from one region to the next, the total production of any one region is limited by the recoverable amounts of the finite resource in that area.

Hubbert used the logistic curve because of its solid theoretical basis, good empirical agreement for a wide array of growth processes and its mathematical tractability [15, 16, 26]. The derivative of the simple logistic curve, commonly known as the Hubbert curve, has been frequently used in oil production forecasting. Analysis regarding the forecasting properties of the simple logistic function, its derivatives and related curves has been performed by others [27-29]. Coal production forecasts based on various curve fits have been done by others [21, 23, 30-32]. In addition, logistic curves and their behaviour have also been used in other energy scenarios in a wide array of different applications [33-36].

2.1 Aim of this study

It is commonly assumed that resources will be transformed into new reserves as demand increases [37, 38]. Historical trends can provide some insight in the validity of this idea and what can be expected from the future. The goal of this article is to investigate the world's coal supply and trends in the assessments of reserves and resources. The result will lead to reasonable estimates on the amounts of coal accessible for future production. Because mining restrictions and other similar limitations are important factors for coal availability, a general idea of how they might develop in the future is also needed to estimate future coal production. Coal that exists but cannot be extracted due to restrictions is irrelevant to future production.

The trends in reserves and resources estimates of coal will also be investigated to observe typical behaviour. Similar studies have already been performed for the USA [23, 32]. Historical trends are assumed to continue and no dramatic deviations are considered. This will provide a complementary view to other studies that have used geological existence as the only factor for future production [37, 38] without closer examination of how volumes available for production have actually developed over time. The modelling uses the basic approach that Hubbert [24, 25] originally proposed to provide some possible future outlooks. Finally, the forecast for coal production will be compared with the forecasts from EIA, IEA and the emission scenarios used by Intergovernmental Panel on Climate Change (IPCC).

2.2 Limitations of this study

The method used here can provide insight into the general long-term flow of finite energy resources but perturbations caused by sudden and unforeseen near-term economic or political changes cannot be predicted. Therefore, long-term life-cycle projections should not be used as a substitute for meticulous economic studies to forecast perturbations in coal production over the next few years or a decade [17]. The projection formed here should not be seen as highly accurate but rather as insight into the long-term trend.

The future development of reserves will be based on extrapolation of the historical trend for reserve and resource assessments. Past influences of socioeconomic factors and technological innovation are incorporated in the historical data on which the outlooks are based and therefore included implicitly. There is a possibility that economics, politics or technology will drastically change coal production from the way seen in history, but that must still be seen as an uncertain outcome. Simple extrapolation is sometimes the only tool available for future outlooks [30]. Consequently, this study will provide only an outlook of how the future could unfold if present trends continue because no major deviations are considered.

Another problem also arises from the unreliability of the data analyzed. Publication of reserve statistics is not only a geological act but also includes elements of economics and politics. It is only the behaviour and trends in official assessments that are analyzed and used. To conclude, there are always significant uncertainties involved with all forms of supply data but by using a sound methodology at least some plausible conclusions can be obtained.

3 Overview of coal

Coal is divided into different ranks depending on the degree of coalification as it matures from peat to anthracite. Low rank coals, such as sub-bituminous coal or lignite, are characterised by relatively high moisture levels and low energy content. Higher rank coals, such as anthracite and bituminous coal, have higher carbon and energy content and less moisture. Local conditions during the coalification process can introduce sulphur, sodium and other pollutants into the coal. Coal is broadly divided into four ranks, namely anthracite, bituminous, subbituminous, and lignite [40, 41]. There are many classification systems used all over the world that each basically uses their own set of definitions [13]. Caution should always be exercised when analyzing global coal accumulations to avoid mixing up different classification schemes. The following energy contents of coal ranks are common, although it should be noted that the ranks tend to overlap.

Anthracite: ***30 MJ/kg***
Bituminous coal: ***18.8–29.3 MJ/kg***
Subbituminous coal***: 8.3–25 MJ/kg***
Lignite***: 5.5–14.3 MJ/kg***

From the non-renewable nature of coal it is clear that the production potential of an area or country is ultimately limited by its geology, as it is impossible to extract more coal than is geologically available. However, concepts such as "*endowment*" or "*potential*" are multifaceted and the actual meaning is disputed by different schools of thought. One school argues that "*resource endowment*" is crustal abundance, while the other school maintains that the concept is relatively meaningless and should be avoided. As always, the truth is located somewhere in between the two extremes. Crustal abundance is solely determined by geological processes, which are reasonably well understood by geologists. Furthermore, the physical in-situ amounts will also be virtually fixed as a result of the slow underlying formation processes, even though reported in-situ estimates might change between assessments as a result of new information.

Available coal accumulations are divided into reserves and resources. Reserves are commonly defined as being proved and recoverable under present technology and economic conditions. Resources include additional discovered, but uneconomic or unavailable amounts together with undiscovered, inferred, assumed, and speculative quantities. This distinction is justified by the idea that over time, and perhaps with new technology and higher prices, production and exploration activities will allow a reclassification of some resources into reserves [37].

The terms resources and reserves are often used synonymously by laymen, but it should be absolutely crystal clear that this is a completely erroneous and misleading practice! Being specific and using the right term is essential to paint a realistic picture in any supply assessment or when planning for a sustainable future.

3.1 Coal reserve and resource classifications

Resources are commonly expressed as in situ tonnage, which is the total amount occurring in place. It can be calculated from the thickness of the deposit, the area of extent and the relative density. Thickness is commonly determined at each point of measurement, while the area is measured on a map or plan. The relative density is normally taken from the section that will be mined, or alternatively it might be estimated using the known average ash content. By using average energy content, it is also possible to state resources on an energy basis. Thomas [13] gives a formula for in situ tonnage:

$$\textit{thickness [m] x area [m}^2\textit{] x relative density [tons/m}^3\textit{] = in situ tonnage [tons]}.$$

At regular intervals, scientists and governmental agencies conduct and publish world coal resource assessments. Sadly, no truly international system is defined and all major coal producers generally use their own system. However, the World Energy Council (WEC) and the Federal German Institute of Geosciences and Natural Resources (BGR) both deal with assessments of global coal reserves and resources. These two sources will be dealt with in greater detail here.

The WEC, consisting of 93 national committees and over 3000 member organizations, collects its information from a coal data survey sent out to all member countries. The survey is then filled in using available national data. It should be noted that the WEC member states make their own interpretations of the definitions to the degree which particular countries' terminology and statistical conventions are compatible with the WEC specifications. The WEC uses the following definitions [42]:

Proved amount in place is the resource remaining in known deposits that have been carefully measured and assessed as exploitable under present and expected local economic conditions with existing available technology.

Proved recoverable reserves are the tonnage within the proved amount in place that can be recovered in the future under present and expected local economic conditions with existing available technology. This includes mining losses and reductions caused by technological constraints.

Estimated additional amount in place is the indicated and inferred tonnage additional to the proved amount in place that is of foreseeable interest. It includes estimates of the amounts that could exist in unexplored extensions of known deposits or undiscovered deposits in known coal-bearing areas, as well as the amounts inferred through knowledge of favourable geological conditions. Speculative amounts are not included.

Estimated additional reserves recoverable is the tonnage within the estimated additional amount in place that geological and engineering information indicates with reasonable certainty might be recovered in the future.

The maximum depth of coal deposits in the WEC assessments varies considerably between member countries. Ukraine reports coal resources to a depth of 1800 meter, while South Africa only reports to depths of 350 m [42]. The minimum thickness of coal seams can also vary considerably between countries, ranging from 25 cm in the USA to 2 m for Romania [42].

The Federal German Institute of Geosciences and Natural Resources (BGR) also compiles estimates of global coal resources and reserves. However, their methodology is somewhat different from the WEC. The BGR defines reserves and resources in the following way [10]:

Resources comprise those energy resources that are either (1) proved but at present not economically recoverable, or (2) are not demonstrated, but by can be expected for geological reasons. For coal, this term is used for all resources in place.

Reserves comprise the portion of energy resources that is known in detail and can be recovered economically using current technologies. This implies that the amount of reserves depends on the current prices as well as on technological progress.

The BGR, depending on the country concerned, includes coals with a maximum depth of 1800 m in its total resource calculations even if 1000 m currently appears to be the lowest depth for economic extraction [37]. Depending on the national limits for the workability of the coal thickness concerned, total resources usually refer to thicknesses starting at 60 cm [37]. The maximum permissible barren partings content in most countries is 35% [37]. Just as the WEC faces, the BGR also has problems with reserve and resource data that is not entirely comparable [43].

The United Nations Framework Classification (UNFC) [44] was introduced in 1997 to improve comparability of reserve and resource categories from different countries. Nötstaller [45] describes this as the first system that has all the attributes for universal acceptance and application. However, since the UNFC does not include deposit defining criteria, such as minimum seam/coal thickness, maximum seam depth, and maximum ash and sulphur contents, the reserve and resource data published by most countries are still not comparable [43].

The *BP Statistical Review of World Energy* publishes proven reserves each year and is frequently used as source material by analysts. Each new edition is published with a listing of "*proven reserves at end year.*" BP simply reproduces the data collected by the WEC [21]. This results in the published proven reserves at end 2008 according to BP in reality being those that were reported by WEC at end 2005. In essence, BP just reproduces the WEC data with certain and misleading time lag, where the reason for this lag is unclear. The BP classification of "*proved reserves*" is identical to the proved recoverable reserves as used by the WEC.

Because of the size of the American coal resources and reserves, their classification system warrants closer inspection. Such studies have already been performed by Höök and Aleklett [23, 32]. Brief overviews of various classification systems used by other countries can be found in Thomas [13].

3.2 Historical supply assessments

Different reserve and resource assessments have been carried out and certain odd features cast doubt on the quality of those assessments, or at least on the quality of their presentation. Large reductions in proved reserves have been made with no explanation in many cases, as well as dramatic changes in the in situ resources. Incomplete data, geological features, generalizations of mining methods as well as terminology mix-ups have been proposed as factors for discrepancies in the US coal assessments [23, 32, 46-47].

Studies of the historical development of resource and reserve assessments are vital for providing better understanding of how trends might evolve. How assessments change over time can also shed some light on their reliability and what kind of changes can be expected in the future. Both the WEC and BGR resource estimates have been published for a reasonably long time period. The first WEC assessment occured in 1924 and the last complete report was published in 2007 (a 2009 interim update is also available). According to the WEC, coal global resources have been around approximately 10 000 Gt for a very long period of time [42, 48-70], although the development after 1995 is unclear since it is not available (Table 1). Regrettably, the WEC stopped providing world resource estimates after 1995 and now gives only resource figures for certain countries. The WEC report from 1980 [62] is of particular interest, since it is prepared by the BGR.

The available BGR dataset spans from 1976 to 2009 [10, 62, 71-78] and can be seen in Table 2. Unfortunately, it is a mixture of data reported in tonnes and as tons of coal equivalent (tce), where a tce is equal to 7000 kcal or 0.697 tons of oil equivalent and converted from metric tonnes for each country based on national heating values [73]. In this study, the BGR estimates expressed in tce were converted to tonnes for easier comparison with the WEC values. A global conversion factor of 0.692 tce/ton was used, which was derived from the average relation between coal production in Mt and Mtoe from 1981 to 2008 as reported by BP [9].

From 1976 to the mid 2000s, world coal resource estimates decreased almost linearly from 10 000 billion tons of coal equivalents (Gtce) to less than 5000 Gtce, a reduction of over 50% [21]. The BGR resource estimates have shown a significant increase after 2005 and have more than tripled since then! This is largely attributed to the addition of coal resources in the USA, China and the Former Soviet Union, but this also coincides with the change of the head of the team writing the annual reports.

In 2005, the BGR reported that they changed coal resource estimates because many countries had insufficient substantiating information and had skipped reporting years. In 2006, *thus far unaccounted prognostic resources* were added in China and Former Soviet Union, leading to a 115% increase in world hard coal resources and a 200% increase in lignite resources. In 2007, the BGR made yet another upward revision, increasing world hard coal resources by 68% and lignite resources by 36%. This was explained by the addition of newly measured, indicated, inferred, and hypothetical coal resources in Alaska identified by a USGS study [79].

It is well worth noticing how the recent BGR reserve estimate for the USA disagrees with the numbers given by the EIA. For 2008, the BGR [10] reports US reserves of 263 Gt, while the EIA states 237 Gt [80]). This is an 11% difference compared to the official American number. For Australia, a similar pattern can be seen where the BGR estimate for 2005 [76] is 35% higher than the number from Geoscience Australia [81] for the same year. However, the BGR has reduced their reserve estimates for Australia in recent years and are now only differing around 1% from the official Australian estimate. It appears as if BGR sometimes has a tendency to report higher reserve estimates than national agencies.

Table 1. *Total resource estimates in Gt for selected countries and the world as published by the WEC. Data sources [42, 48-70]*

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1924	5 398	996	79	n.a	166	56	423	19	190	n.a	7 398
1929	3 829	1 213	79	489	166	58	423	n.a	190	n.a	n.a
1937	2 893	10 113	26	611	171	214	427	68	306	n.a	16 025
1948	2 897	n.a	n.a	n.a	n.a	90	n.a	n.a	n.a	n.a	n.a
1974	2 925	1 000	83	5 714	199	44	317	61	163	3	10 754
1976	3 600	n.a	86	6 948	372	93	n.a	n.a	190	3	11 724
1980	1 073	1 463	115	6 007	860	93	295	186	190	19	13 476
1986	1 570	2 737	115	5 502	785	133	332	197	186	23	11 990
1989	1 570	1 094	245	5 487	821	122	332	198	378	6	10 052
1992	1 570	954	245	5 487	821	122	241	207	378	64	10 236
1995	1 216	954	286	5 487	817	126	269	223	190	64	10 567
1998	1 570	n.a	n.a	4 141	454	126	308	74	n.a	n.a	n.a
2000	1 321	n.a	n.a	n.a	435	116	308	65	n.a	n.a	n.a
2004	1 564	n.a	n.a	n.a	431	115	100	170	n.a	46	n.a
2007	1 560	n.a	290	n.a	n.a	115	50	56	n.a	57	n.a

Table 2. *Total resource assessments in Gt as published by the BGR. Year 1980 is seen as identical to the WEC report from the same year. Data sources [10, 62, 71-78]*

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1976	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	14 185
1980	1 073	1 463	115	6 007	860	93	295	186	190	19	13 476
1988	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	11 610
1993	1725	935	201	5493	861	155	380	194	447	42	10 994
1998	1478	766	166	5499	371	55	371	168	227	18	9 636
2001	1 122	668	163	2 217	194	5	264	144	190	24	5 424
2004	1 090	1 090	259	2 295	298	164	88	70	5	11	4 668
2005	1 058	1 090	292	2 326	305	164	91	101	7	65	6 039
2006	1 359	4 367	252	2 915	194	49	85	179	190	27	9 554
2007	6 720	4 367	230	2 931	148	29	83	179	187	24	15 511
2008	8 120	5 509	278	4 336	359	31	191	401	188	93	20 767

Table 3. *Recoverable reserve estimates in Gt for selected countries and the world as published by the WEC. Data sources [42, 48-70]*

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1924	5 398	996	79	n.a	166	56	423	19	190	-	7 398
1929	3 829	1 213	79	489	166	58	423	n.a	190	n.a	n.a
1937	n.a	n.a	5	309	9	8	109	15	130	n.a	691
1948	n.a	n.a	n.a	n.a	n.a	22	n.a	n.a	n.a	n.a	n.a
1974	182	80	12	136	n.a	11	65	23	4	1	591
1976	199	n.a	13	n.a	63	18	64	n.a	45	0	n.a
1980	182	140	84	233	59	33	60	39	45	1	882
1986	264	n.a	n.a	245	66	58	80	43	5	n.a	839
1989	215	731	63	241	91	55	80	40	4	3	1 598
1992	241	115	63	241	91	55	80	41	4	32	1 039
1995	241	115	70	241	91	55	67	42	3	32	1 032
1998	247	115	75	225	90	55	67	14	2	5	984
2000	250	115	84	225	82	50	66	22	2	5	984
2004	247	115	92	222	79	49	7	14	0	5	909
2007	243	115	56	222	77	48	7	8	0	4	847
2009	238	115	59	222	76	30	7	8	0	4	826

Table 4. *Recoverable reserve estimates in Gt as published by the BGR. Year 1980 is seen as identical to the WEC report from the same year. Data sources [10, 62, 72-78]*

	USA	China	India	FSU	Australia	South Africa	Germany	Poland	UK	Indonesia	World
1976	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	792
1980	182	140	84	233	59	33	60	39	45	1	882
1988	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	880
1993	282	110	62	48	84	68	53	22	3	6	818
1998	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	806
2001	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	968
2004	283	115	125	206	105	49	7	10	0	5	990
2005	252	115	126	157	107	49	7	10	0	7	935
2006	247	192	96	204	79	49	41	16	0	7	1 019
2007	263	192	74	215	77	29	41	16	0	7	990
2008	263	192	81	215	77	31	41	16	0	4	997

3.3 Discussion on historical trends

The WEC coal resources have varied between 10 000 and 16 000 Gt since 1937, often closer to the lower level of this interval. For comparison, the BGR resource estimates were around 10 000 Gt in early 1980s, before a successive reduction ending in 2005. Significant variations can occur in both datasets, but the general picture is still dominated by the Big Six. In recent years, the trend has been that several countries are unable to adequately report resource numbers. Thus global WEC estimates after 1995 have been impossible to make. In contrast, the BGR has compiled global resource estimates for a shorter period of time. Recent years have even taken the BGR estimates to an all-time high but it is questionable how much of this increase is reliable as much seems to be unaccounted prognostic, hypothetical or uncertain coal amounts.

Coal resources have been described as largely an academic figure since it includes deep and poor quality coals [46]. Clearly, there is no substitute for a good geological understanding of depositional systems associated with coal deposits and of adequate data for coal resource estimates. The estimate of coal reserves, which must follow the resource estimates, is more complex and involves consideration of numerous economic, technical, legal, and social parameters, relative to specific markets for coal, during a present period of great economic and regulatory uncertainty [46]. This is a challenging pursuit and the significant changes in reported reserves indicate how hard it is to make reliable estimates (Table 3 and 4). Restrictions on high-sulphur coals, various mining and land regulations have prevented coal quantities from being extracted, despite the fact that they are economically feasible. This has been closely investigated for the USA [23, 32], where it was found that restrictions played a major role in limiting the amounts available for production.

Early WEC-data clearly shows the lack of distinction between resources and reserves, but since 1938 this issue seems to have been resolved. Global reserves have varied between 600 to 1600 Gt, where the latter is a rather extreme outlier caused by a massive reserve increase in China that later was revoked. Since 1950s, world coal reserves according to WEC have been between 800 to 1000 Gt, with a steady declining trend since early 1990s (Table 3). In comparison, BGR reserve numbers have been fairly constant at around 900 Gt since 1976 (Table 4). In contrast, BGR reserve data do not have a decreasing trend over the last two decades. In both cases, the historical trend does not point toward any major increases in world coal reserves. In the best case, the reserves can be fairly stable, while they can continue to decrease in a less optimistic case.

The overall conclusion one also can draw from the historical trends in the reserve and resource assessments is that the reported data should not be regarded as an accurate assessment of available coal volumes for production. The important thing is rather the evolution of resources and reserves that give an indication of the general trend that can be expected to determine the long-term behaviour.

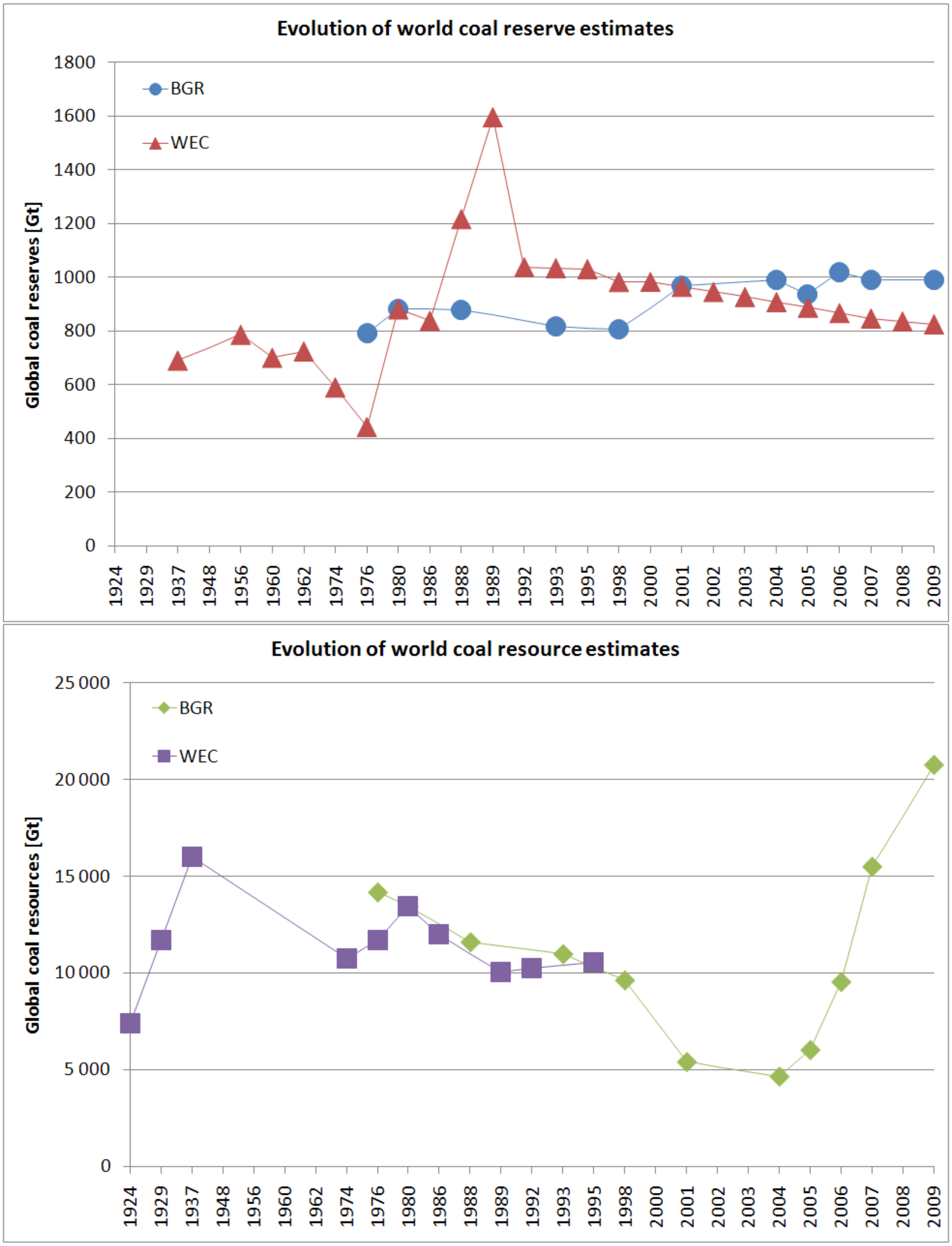

Figure 3: *Evolution reserve and resource estimates from the WEC and the BGR. World coal resources have been declining in reports since 1937 except for the recent BGR increases. Coal reserves have been steady or in decline since the late 1980s.*

3.4 Model constraints for future production

Based on the evolution of the world coal resource and reserve estimates, it is not assumed that the future will have dramatically different conditions compared with the present situation. To conclude, the historical trend does not point toward a dramatic increase in the available amounts of coal — rather the opposite. Major relaxations of restrictions or regulations are not expected in the future. The approach here is just a basic first step to show how much the available coal volumes can contribute to future production under reasonable assumptions derived from historical experience. If additional restrictions are pursued, which is possible from the current political setting, the available volumes for future production could even be less than what is currently reported in official statistics.

A logistic curve, limited by a suitable estimate of ultimate reserves, is used for the modelling of future coal production, as originally used by Hubbert [24, 25]. An estimate of the ultimate reserves was derived by adding cumulative production to reasonable recoverable reserve estimates obtained from the evolution of historical assessment. This approach is discussed in more detail [23, 32].

Historical production data was used for curve fitting. Sometimes it was necessary to compensate for major historical events, such as the fall of the Soviet Union, that had a major effect on production. Instead of using two logistic curves as in [12], only one was used in this study since it was hard to locate equally long historical production series for all countries. The WEC reserve estimates, and the production data published by BP [9], are mainly used in this study due to their dominating role as reference material. Using the BGR reserve estimate does not change the picture significantly.

In the standard outlook, the logistic curve was limited by the cumulative historical production plus the proved reserves (as of 2009). This provides a reasonable long-term perspective on how much future production can be expected from the known reserves. To provide an alternative and more "*optimistic*" view, the reserves were assumed to be twice as large as reported in the high case. In essence, this case depicts a future where the world proved coal reserves are bigger than currently known or where some resources will be transformed into reserves. There is a significant difference in future production levels, although the peak year does not change significantly (Figure 4). Even a doubling of the recoverable reserves won't change their duration notably if there is an underlying exponential increase in the extraction, as described by logistic growth.

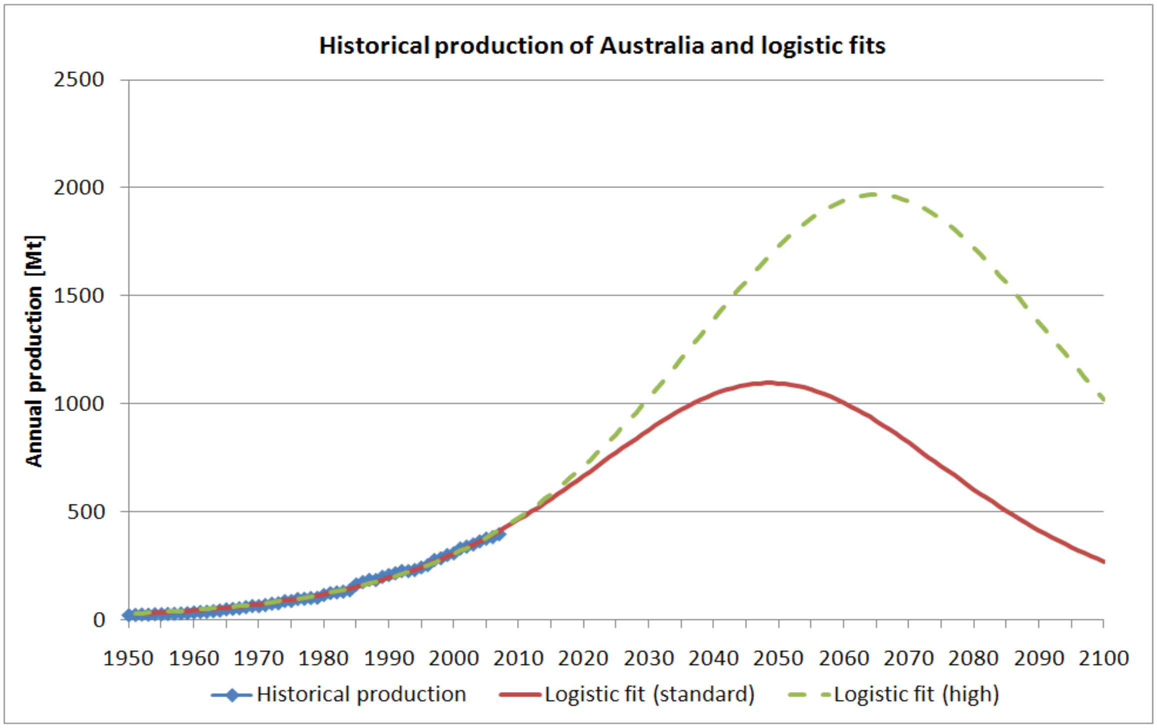

Figure 4: *Historical production of Australia together with logistic fits. Here, the logistic model is used to create a possible future production. Assumed ultimate reserves are 85 and 162 Gt. Doubling of the reserves only postpones the peak year by 16 years but the difference in production level at the peak year is over 40%.*

4 Global coal production outlook

Each country's future coal production was modelled using logistic curves. Future global coal production outlooks were then created from the country-by-country analysis (Figure 5). Mexico is included in South & Central America. Ukraine is included in Europe & Eurasia and is responsible for the majority of the production from this region in the future, as most European and Eurasian countries have small reserves and most of these are already in decline. The two cases are displayed in more detail in Figure 6 and 7.

From the results it can be seen that global coal production will be able to increase over the next decades by about 20% in the standard case, mainly driven by China, India and Australia. A plateau will be reached around 2025 in the standard case and global production will go into decline after 2030 (Figure 6). Russia will end up as the last important coal producer, which is reasonable due to vast but remote reserves located in Siberia. China will suffer a comparatively fast decline after a peak production around 2025, which is roughly in line with the results of other studies [30, 31]. The USA will flatten out at nearly 1400 Mt and will be able to keep a virtually constant production volume during the remainder of the century, which agrees with [12, 32].

There is a possibility that significant shares of the world’s coal reserves are overestimated as many assessments are old, especially within the Big Six, and if the present trend of decreasing coal reserves continues. The decline in world coal production might be steeper than shown in figure 6.

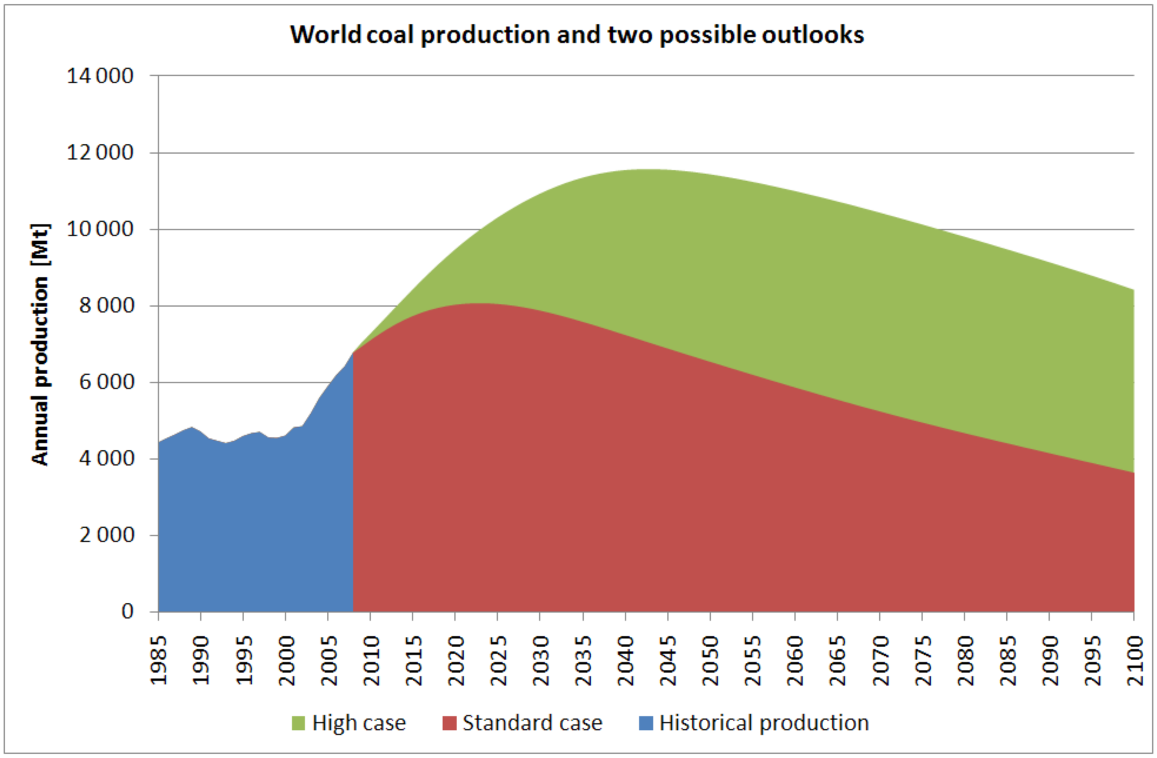

Figure 5: *Historical world coal production and two possible outlooks based on logistic models.*

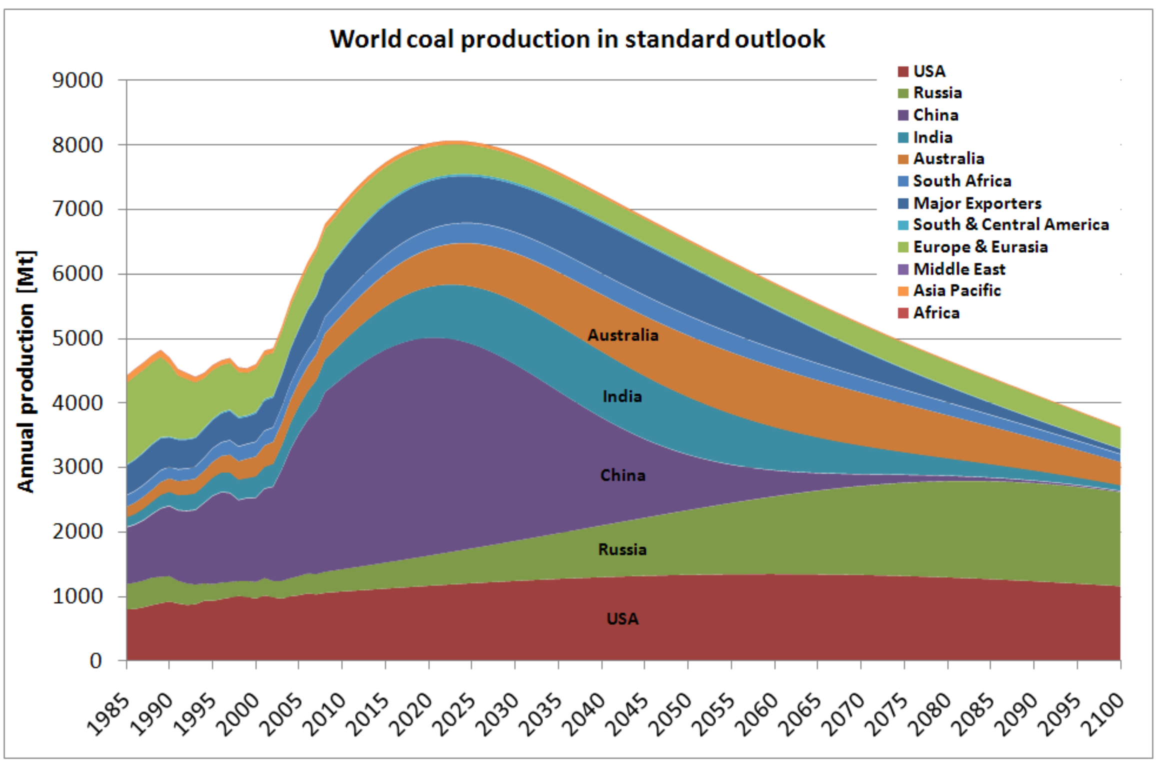

Figure 6: *Standard case outlook for future global coal production.*

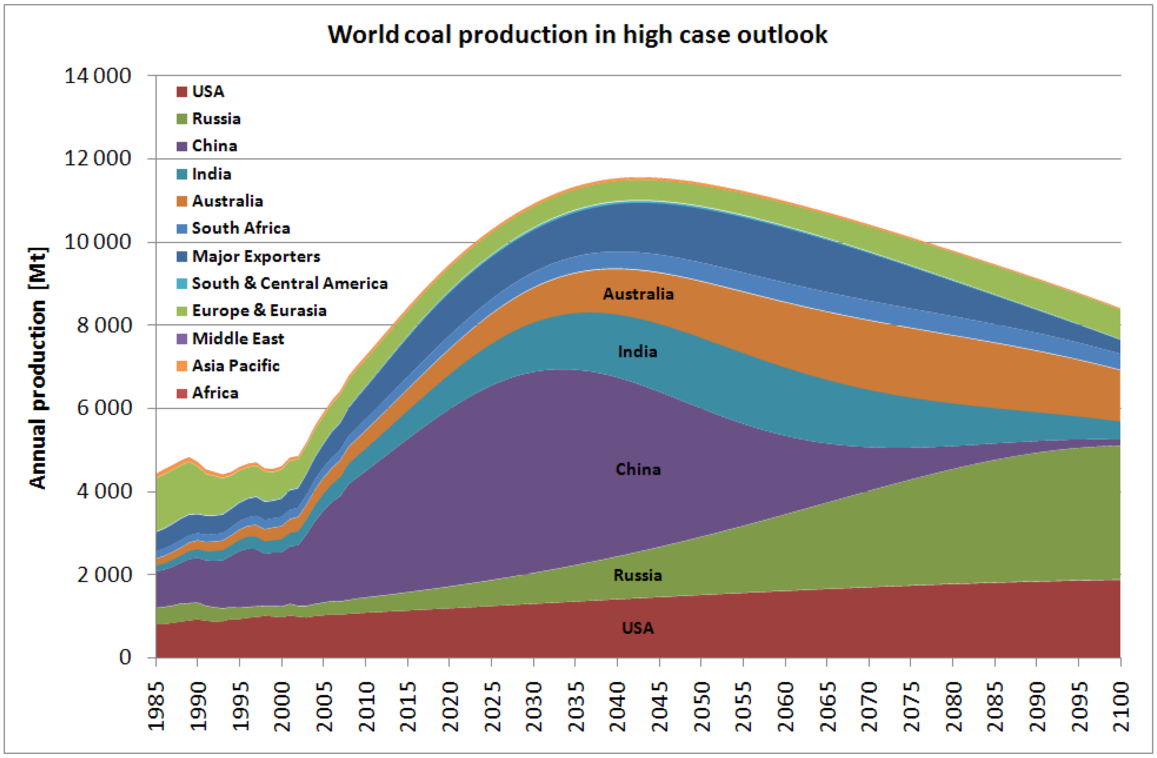

Figure 7: *Even if the world's coal reserves are twice as large as reported this does not postpone the peak in production more than two decades. The Big Six would still dominate future production, given their dominance in coal supply. China, India and Australia will be the driving forces behind global coal production.*

4.1 Comparison with other forecasts

Conversion to energy units was performed individually for each country using approximate conversion factors derived from BP [9]. This also attempts to reflect the actual differences in conditions, such as the high ash content of coals from India. The overall shape and production levels are in line with the results obtained by Mohr and Evans [84], which used similar ultimate reserve constraints but employed a more complex model capable of replicating real world mineral exploitation with supply and demand interactions. This is seen as an indication that a simple model, such as logistic curves, can yield results comparable to a more intricate model under similar constraints.

The standard and the optimistic case were also compared with the reference scenarios from EIA [82] and IEA [83] (Figure 8). It is possible for world production to meet the reference scenarios in both forecasts until around 2015 in the standard case. Beyond this point, the standard case is not compatible with any of the coal forecasts from EIA or IEA. However, the high case is compatible with both EIA and IEA projections, but one should keep in mind that this requires the world coal reserves to double from their present levels. This is not likely, given historical trends in reserve and resource assessments, but not impossible if extensive new exploration programs are undertaken or restrictions limiting mining are removed on a large scale. Emissions issues and increased environmental concern instead indicate that additional measures will be taken to reduce coal's use as a future energy source.

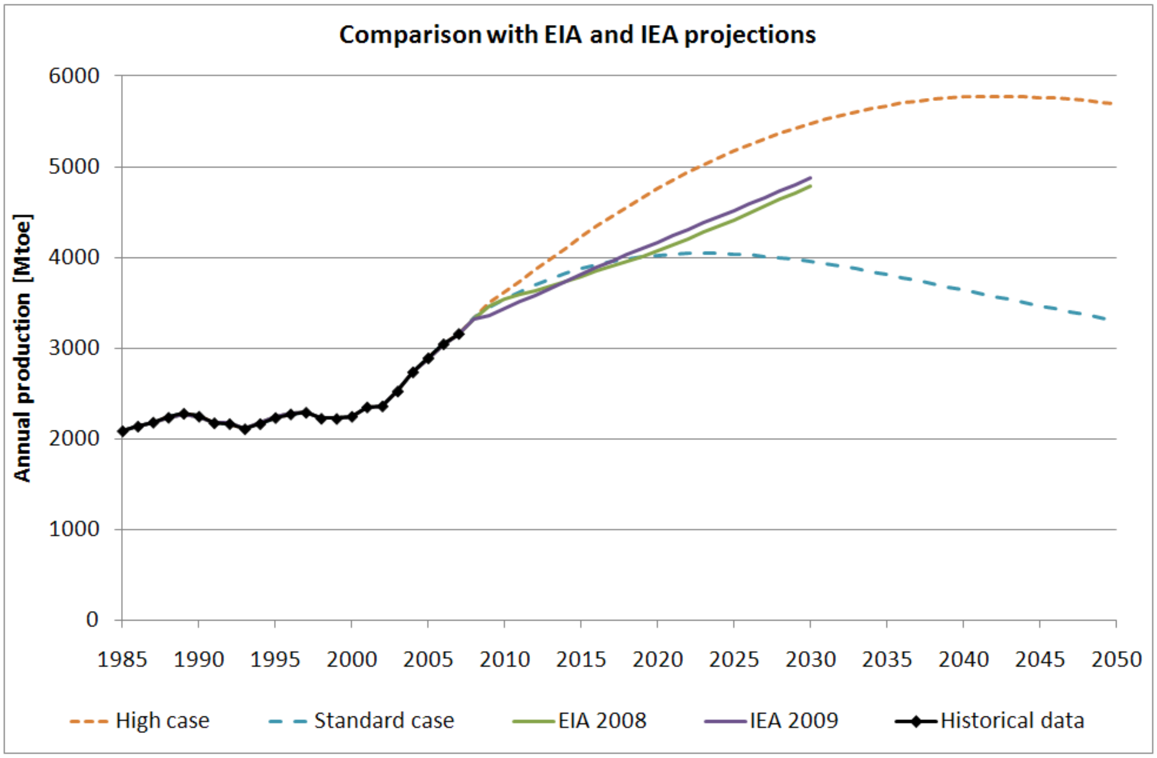

Figure 8: *Comparison with the forecasts from IEA and EIA. Already by 2015 the standard case starts to diverge from the IEA/EIA forecasts. Until 2030, both IEA and EIA agree quite well with this study, however in the long term a significant difference would probably occur.*

The difference between the standard and high cases is also significant when compared with the IPCC emission scenarios [38], as a number of emission scenarios use huge amounts of coal and have very high future production levels. Some scenarios seem to assume that coal production can keep on growing for the entire century without showing any signs of slowing down. The IPCC projects huge increases in future produced volumes, which must chiefly come from the Big Six, given their dominance in both coal reserves and resources.

Combined with other studies of oil and gas consumption and production in emission scenarios [85-88] it points to the fact that the entire production profile for fossil fuels seems to be very optimistic, apparently unworkable or even purely imaginary. Many assumptions regarding future production of fossil fuels should be revaluated if more realistic availability and production behaviour should be taken as parameters for future production instead of only geological existence. The current emission scenarios [38] should not be regarded as based on a realistic availability of coal for production as they seemingly ignore all forms of mining restrictions and generally only take geological existence as the determining factor for long-term future production forecasts.

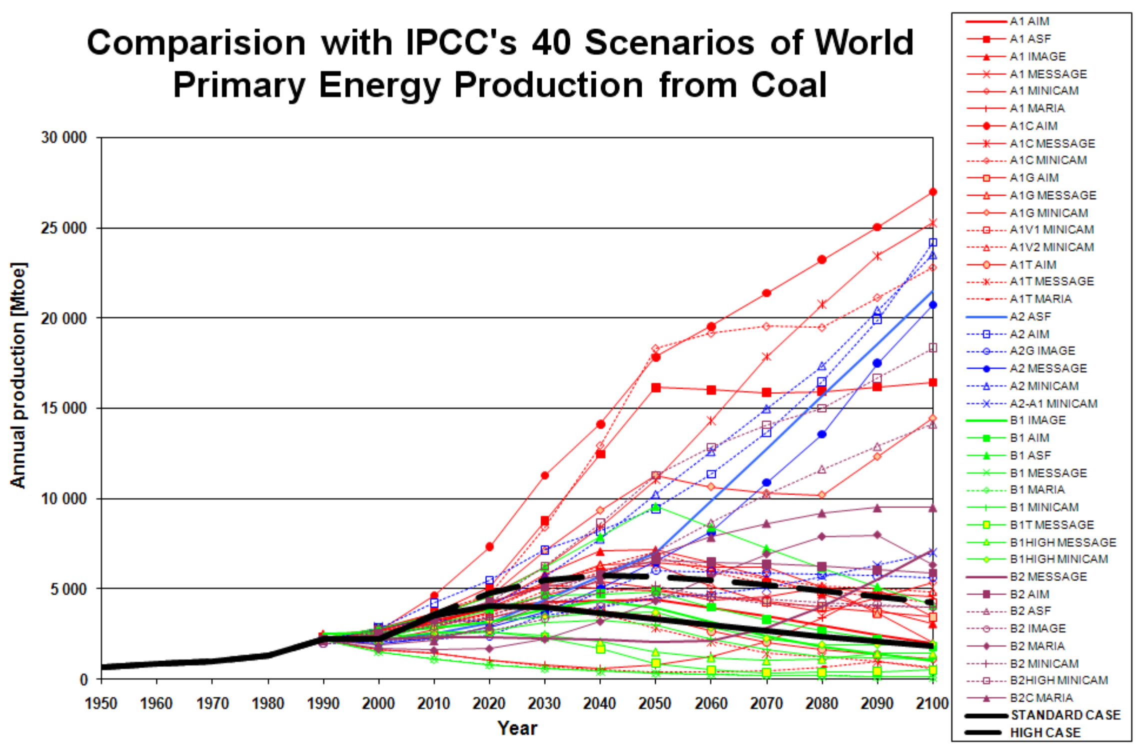

Figure 9: *Primary energy production from coal in the IPCC emission scenarios, compared with the forecast based on the available coal reserves. The coloured lines represent various scenarios from the IPCC. Some do not even show any signs of halting growth this century! Many of the scenarios use much more coal than is realistically available. Only the more environmentally friendly scenarios lie beneath the standard case whereas the optimistic case is compatible with some more scenarios.*

5 Conclusions

From a simple survey of reserve and resource assessments for almost a century, and a more detailed examination over the last three decades, it can also be found that estimates are of poor quality. Resources have undergone significant changes, mostly downward. The recent increase reported by the BGR [10] should be seen as speculative instead of definite. In addition, it is clear that the (assumption or premise) of having coal resources unequivocally converted to reserves does not seem to be supported by published data on a global level. It is recommended that more comprehensive analyses of global coal resources and how they can converted to reserves are pursued, but this is work for another study. Obtaining a realistic picture of the future potential for coal resource to be upgraded to economically competitive reserves is needed for a more detailed forecast.

Both reserve and resource data have shown major fluctuations, generally downward, and cannot be seen as an accurate estimate of recoverable amounts of coal. In summary, coal assets require a closer assessment and a more realistic picture of proved reserves needs to be established. Better data and a more transparent and reliable system for reserve evaluations is necessary to form a solid basis for long-term decisions and forecasts regarding the global energy system. The variations in reserve estimates are many, everything from changes in economic conditions and introduction of various restrictions to more accurate geological mappings. Restrictions do play a major role in determining coal availability for production as shown in the USA [23, 32].

Russian coal reserves have been constant in international statistics since 1996 and the change in FSU originates from Ukraine and Kazakhstan. Maleshev [89] states that the Russian coal reserves are based on data obtained in the 1950s and 1960s and that those do not reflect current requirements on mine design and outfitting. According to the best estimates by experienced geologists, mining engineers, and economists, around 40% of the Russian reserves cannot be regarded as of any practical interest because they are highly unprofitable [89]. Evidently, Russia is in need of closer future investigation.

China will likely determine the timing of the peak in global coal production due to its dominating role as a producer. Aden [90] performs a closer survey of the Chinese coal situation and points to recent reserve updates from Chinese authorities from 2003. However, those new numbers have not reached the WEC yet, while the BGR reports a somewhat larger reserve number. Chinese coal reserves have not been updated in the WEC statistics since 1992, while the BGR has an upward revision after 2005 (Table 3 and 4). For consistency, this study has used 114.5 Gt as reserves for China but others have explored production outlooks using higher reserve numbers [30, 31]. Regardless of the assumed Chinese reserves, both this study and others [30, 31] give a Chinese maximum production around 2025. In any case, China is a source of uncertainty in any forecast.

Given the historical development of restrictions and the increased concern for the environment, it may be that restrictions are strengthened further in the future. If this is the case, current reserves will turn out to be overestimated and future production could even be less than projected in Figure 6. The poor quality of the internationally available data is problematic for reliable outlooks and the future remains uncertain. Detailed studies of the Big Six are especially encouraged to form a reliable base for production outlooks. Most of the coal is located within the Big Six, which also make up most of the world's coal production [9, 10]. Therefore, the Big Six and their future development will determine the general shape of the future global coal production.

Logistic curves offer more possibilities than just being an instrument for future outlooks. They can also provide a simple tool for resource management to determine what might happen to future production *if resource availability poses a problem*, regardless of the geological, practical or political origin of the availability limitation [47]. In the light of peak oil and the awareness of natural resources for continued well-being of society and mankind, resource management should play a large role in future planning. Consequently, the future outlooks provided here can also be seen as future scenarios where coal utilization has been limited by political decisions.

Long range forecasting methods can provide a useful insight into what can be expected further into the future but does not replace short term forecasts [17]. However, the outlooks obtained here are well in line with the results from a model based on real world mineral exploitation with supply and demand interactions [84] under similar resource constraints. This may also be seen as an example of how simple mathematical curves can agree well with more complex models.

According to this study, a global peak coal can be expected between 2020 and 2050, based on the size of the recoverable reserves (Figure 5). The standard case, i.e. the actual reported reserves, is large enough to sustain increased production for a few decades before the peak is reached 2020-2030 (Figure 6). This is much sooner than commonly thought, and if this is correct it would represent a significant challenge for future energy supplies. Even if the world's recoverable coal volumes are twice as large as reported – the high case – the peak would only be postponed until 2030-2050 (Figure 7).

Even if the reserves are wrongly estimated by 100% the general picture does not change significantly. A peak in global coal production can be expected well before 2100 unless reserves turn out to be significantly larger than reported or if resources are transformed into reserves on a major scale hardly seen before in history. To avoid a peak within a few decades, extensive new exploration or removal of mining restrictions must be undertaken unless the reserves are larger than reported. Alternatively, developments of alternative energy sources should be pursued.

It can also be concluded that the outlooks from the EIA [82], the IEA [83] and the IPCC [38] diverge from what the known reserves can actually provide. This calls for further investigation and maybe a revision of these forecasts. Sadly, both IEA and EIA end their projections by 2030 and the long term differences cannot be compared.

The impact on the emission scenarios used in climate models for anthropogenic global warming is also an important issue that needs to be addressed. The current emission scenarios [38] should not be regarded as a realistic view of how future coal production might behave as they effectively ignore everything other than geological existence as determinants for future production [87]. Especially the highest emission scenarios, where world production is expected to be roughly ten times the current output by 2100, appears as implausible and would require extreme future production from the Big Six. A reassessment of emission scenarios should be made with more reasonable assumptions about the future fossil fuel production.

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