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Trends in U.S. Recoverable Coal Supply Estimates and Future Production Outlooks

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Abstract:

The geological coal resource of the U.S. is abundant and proved coal reserves are listed as the world's largest. However, the reserves are unevenly distributed and located in a small number of states, giving them major influence over future production. A long history of coal mining provides detailed time series of production and reserve estimates, which can be used to identify historical trends. In reviewing the historical evolution of coal reserves, one can state that the trend here does not point towards any major increases in available recoverable reserves; rather the opposite is true due to restrictions and increased focus on environmental impacts from coal extraction. Future coal production will not be entirely determined by what is geologically available, but rather by the fraction of that amount that is practically recoverable. Consequently, the historical trend towards reduced recoverable amounts is likely to continue into the future, with even stricter regulations imposed by increased environmental concern.

Long-term outlooks can be created in many ways, but ultimately the production must be limited by recoverable volumes since coal is a finite resource. The geologic amounts of coal are of much less importance to future production than the practically recoverable volumes. The geological coal supply might be vast, but the important question is how large the share that can be extracted under present restrictions are and how those restrictions will develop in the future. Production limitations might therefore appear much sooner than previously expected.

Key words: US coal reserves, future production, peak coal

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1. Introduction

Natural resources are vital in supporting the continued well-being of the world's population. Metals, fossil fuels, minerals and other resources are critical components for the modern society. Conceptually, fossil fuels and minerals are non-renewable resources. This implies that once depleted a mineral deposit no longer represents a source of material. In comparison, agriculture, forestry and fishery resources are renewable and can supply sustained harvests, provided that the annual extraction rate doesn't exceed the regrowth.

Of all available resources, none are as important as energy. In fact, energy has been described as the ultimate resource by numerous studies (Ehrlich et al., 1970; Perry, 1971, Cook, 1977). In physics, energy is defined as “*the ability to do work*”. Einstein (1905) even showed the equivalence between energy and mass, implying that everything in the universe is made from energy in various forms. Naturally, it follows that energy influences everything and cannot be substituted for other resources. Bromley (2002) put this in a greater perspective and wrote the following: “*Energy is the ultimate resource; with abundant energy we can recycle indefinitely the elements of the earth's crust for our repeated use; we can fix nitrogen from the atmosphere; we can liberate phosphorus from the rocks, and we can have unlimited pure water through desalinization of sea water or pumping from deep aquifers; with all this we can then maintain agricultural economies beyond anything of which we have even dreamed as yet.*”

The rapid growth of fossil energy output after World War 2 coincides with the green revolution in agriculture and the utilization of high yield agricultural techniques based on synthetic fertilizers and high energy use. In fact, fossil energy has been described as the principal raw material of modern agriculture (Pimentel et al., 1973; Green, 1978; Pfieffer, 2006; Pimentel, 2007). Furthermore, energy is intimately linked to economic growth and development. Studies have found that energy consumption has a significant positive long run impact on economic growth (Akinlo, 2002) and connections between energy and real output (Hondroyannis et al., 2002; Payne, 2010a, 2010b). To summarize, nothing is as important to society as energy.

Energy resources take many forms, ranging from fossil fuels or uranium to biomass, human labour or wind power. Currently, over 80% of all primary energy used by mankind is derived from fossil fuels (IEA, 2008). Petroleum dominates with roughly 35% of world primary energy, with coal as number two (~26%), followed by natural gas (~21%). The contributions from other energy sources range from 2-10% (biomass, nuclear, hydropower) to less than 0.1% (wind, solar).

1.1 Aim of this study

This study is largely based on the previous work of Höök and Aleklett (2009) where historical assessments were compiled in order to show trends in estimated U.S. recoverable coal volumes. That work is extended here to include further discussion of what coal amounts that can be realistically available for production in the future and how this might affect future energy policies. Additionally, further expansion of the production modeling framework is performed by incorporating new curves for future outlooks and integrating depletion rate analysis as an additional parameter.

2. Coal resources, reserves and recoverable volumes

From the non-renewable nature of coal it is clear that the production potential of an area or country is ultimately given by its geology. Naturally, it is impossible to extract more coal than geologically available. However, concepts such as “*coal endowment*” or “*coal potential*” are multifaceted and the meaning of such terms is disputed by different schools of thought. One school argues that “*resource endowment*” is crustal abundance, while the opposite school states that the concept is relatively meaningless for supply assessments and should be avoided. As always, the truth is located somewhere between the two extremes.

Crustal abundance is solely determined by geological processes, which are reasonably well understood by coal geologists. Furthermore, the physical in-situ amounts will also be fixed, even though they might change in reports as a result of new information. The USGS use the following definition (Wood et al., 1983):

Coal resources *are naturally occurring concentrations or deposits of coal in the Earth's crust, in such forms and amounts that economic extraction is currently or potentially feasible.*

This category is divided into a number of subdivisions depending on geological certainty or other properties. Technology and proper investments can, at least in theory, recover all available in-situ coal if required economic conditions exist. In essence, this definition reflects crustal abundance of coal. EIA uses essentially the same definition for coal resources. However, resource numbers are relatively inadequate as they neither take economics into account nor include fundamental properties of energy source utilization or legal issues. Recoverability is the crucial property for production and this leads to a variety of attempts to express the recoverable volumes of coal.

The economist Adelman (1990) has stated that the amount of mineral in the earth is an irrelevant non-binding constraint to production and the amounts left in the ground are probably unknowable but surely unimportant and of no economic interest. This is correct in the very limited sense that we will never recover the very last amounts of coal or any other resource from the earth, implying that the ultimate recovery is undefined and governed by non-geological circumstances. However, the recovery factor might be undefined, but it does not make it unlimited. It is bound between zero and 100 percent of the crustal abundance, which is clearly defined but not known exactly. Thus, the fact that the amount of recoverable coal is “*undefined*” and unknown cannot be an argument against the existence of a production peak at some point or the future production limitations imposed by the inherent finiteness of coal.

Recoverable volumes are affected by many factors, making them dynamic. Higher prices, new exploration or improved technology yield increased amounts of recoverable coal. In a similar way, increased freight rates, extraction costs or introduction of various restrictions can decrease recoverable volumes. Likewise, political influences can greatly influence demand patterns.

Not all coal can be recovered from a coal bed and some amounts will be unavoidably lost. This includes coal that is (1) left to support underground mine roofs, (2) used as barrier pillars adjacent to the mine or property boundaries, or (3) simply left because of other reasons. See Wood et al. (1983) for more examples of mining losses. Mining and production practices also put constraints based on thickness, depth, rank and other properties to the recoverable amount of the in-situ resource. USGS has chosen the following definition for the reserve base:

Reserve base: *those parts of the identified resources that meet specified minimum physical and chemical criteria related to current mining and production practices, including those for quality, depth, thickness, rank, and distance from points of measurement. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. The reserve base may encompass those parts of a resource that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic, marginally economic, some of those that are currently subeconomic, and some of the resources that have been or will be lost-in-mining but whose attributes indicate possible future recovery.*

The EIA uses a more specified definition compared to the broader USGS scheme (Annual Coal report, 2007).

Demonstrated reserve base: *a collective term for the sum of coal in both measured and indicated resource categories of reliability which represents 100 percent of the coal in these categories in place as of a certain date. Includes beds of bituminous coal and anthracite 28 inches or more thick and beds of subbituminous coal 60 inches or more thick that occur at depths to 1 thousand feet. Includes beds of lignite 60 inches or more thick that can be surface mined. Includes also thinner and/or deeper beds that presently are being mined or for which there is evidence that they could be mined commercially at this time. Represents that portion of identified coal resources from which reserves are calculated.*

Two important restrictions are legal prohibitions of coal mining in certain areas and/or the use of a particular mining methodology, such as longwall mining. This can prevent extraction of coal, despite that the coal might be technically and economically recoverable. For example, land-use regulations and federal laws prevent mining near homes, public buildings or federally funded highways (Eggleston et al. 1990). Accessibility, availability and restriction factors are linked to the society and its legal/political climate, and can have major influence on the recoverable volumes. To include restrictions and accessibility, EIA utilizes the following definition:

Estimated recoverable reserves: *cover the coal in the demonstrated reserve base considered recoverable after excluding coal estimated to be unavailable due to land use restrictions or coal currently economically unattractive for mining (and after applying assumed mining recovery rates).*

This category corresponds to proved reserves according to BP (2009) or the proved recoverable reserves used by World Energy Council (2007). EIA creates this category by applying economic feasibility criteria factoring downward from the DRB. The “coal reserve” term used by EIA may better be described as “potential coal reserves”, as they are generally not proved by detailed drilling (American Association of Petroleum Geologists, 2007). In comparison, USGS (Wood et al., 1983) uses the following terminology:

Reserves: *Virgin and/or accessed parts of a coal reserve base which could be economically extracted or produced at the time of determination considering environmental, legal, and technologic constraints.*

A full discussion of coal resources and reserve terminology, as used by EIA, USGS, and U.S. Bureau of Mines, can be found in EIA (1996). Detailed discussions of how availability of recoverable coal is estimated by the USGS can be found in Carter and Gardner (1989), Eggleston et al. (1990), or Luppens et al. (2006).

2.1 What matters for future coal production?

For near and medium term future outlooks, coal will remain an integral part of the US energy system. Consequently, future coal production is a topic of major importance. Future production is dependent on practically recoverable coal volumes, i.e. the amounts that are available for commercial production. This is simply the coal amounts that can be extracted with present and future technology under accompanying economic and legal conditions. Coal reserves are only useful to society as a production flow (solid fuel, coal bed methane, feedstock etc), since unmined coal beds provide little of economic or practical benefit.

The situation is similar to that of peak oil, where Skrebrowski (2008) explained that consumers need delivery flows, while oil reserves are only useful as production flows. Consequently, peak oil is when production flows can't meet the demand. In summary, talking about either size of reserves, oil formation theories or about access to reserves, while ignoring flows is to greatly miss the very core of peak oil theory. Equivalently, focusing on future coal reserves, while ignoring other factors that affect coal extraction, is unreasonable and leads to an incomplete picture for future coal production.

As an example, one may take the Gillette coal field in Wyoming and USGS' comprehensive investigation of its coal supply. Luppens et al. (2008) 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 definitively have the largest impact, reductions caused by technical and availability restrictions are also significant.

Coal-in-place estimates are generally very poor indicators of what amounts 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 those factors are properly treated, any effort to provide a future production outlook will be resting on loose foundations.

An attempt to develop a suitable methodology for describing recoverability was carried out by Rohrbacher et al. (1993). They concluded that past estimates of coal in the ground did not address the amount that might realistically be available for production after environmental and technological restraints are considered and highlighted how the Clean Air Act amendments of 1990 (Environmental Protection Agency, 1990), mine reclamation legislation and regulations, new safety and health standards with their associated taxes and advancements in mining

technology had changed the economic competitiveness of certain coal fields. More importantly, Rohrbacher et al. (1993) states that the ample EIA demonstrated reserve base would be far less in reality than that reported if the effects of mined-out prime reserves, environmental, industrial, economic, and social considerations are assessed and the technical aspects of the minability and washability of the individual seams were considered.

Second generation assessments of available coal amounts in the Pittsburgh coal bed has been performed and described by Watson et al. (2001). About half of the original coal resource in place has been extracted, leaving 15 Gt as remaining resources that are increasingly restricted due to the environment, population and technology. Watson et al. (2001) assert that only 3.6 Gt is unavailable due to restrictions and conclude that future coal production from this area is dependent on a complex set of factors, including future transportation costs and environmental policies.

2.2 Technological progress and future coal prices

Resource limitations are conceptually present and will ultimately apply to human activities on the Earth. Furthermore, thermodynamics and energy balance relations will ultimately put limits on all energy sources. For obvious reasons, any energy source must yield more energy than they require for functioning. Otherwise, they would be “*energy sinks*” and would not be able to deliver any useful energy to users or society. This leads to the basic definition of *energy-returned-on-energy-invested* (EROEI) as shown in Equation 1. More comprehensive discussions on EROEI-theory have been done by others (Bullard et al., 1978; Cleveland et al., 1984; Spreng, 1988; Cleveland, 2005; Gately, 2007).

$$EROEI = \frac{\text{Usable Energy Acquired}}{\text{Energy Expended}} \quad (1)$$

Coal production requires an energy input to power machines, workers and other parts of the extraction process. At some point, coal seams will become too thin, located too deep, or containing too much non-combustible material to repay the energy investment needed for recovery of the coal. Required energy investment is an as an underlying factor that will be dominate over all other factors. However, this is not a problem for coal as it is generally superior in terms of EROEI compared to other conventional and unconventional energy sources (Cleveland, 2005). Conceptually, it is still important to remember the fundamental limit that EROEI puts on coal extraction and other energy resources. Hubbert (1982) wrote: “*there is a different and more fundamental cost that is independent of the monetary price. That is the energy cost of exploration and production. So long as oil is used as a source of energy, when the energy cost of recovering a barrel of oil becomes greater than the energy content of the oil, production will cease no matter what the monetary price may be*”.

Human ingenuity has achieved countless breakthroughs in history and current mining technology is able to handle much larger production volumes efficiently. Long wall mining machines and other techniques have greatly aided coal production. Such advances are reviewed by Pinnock (1997). However, other studies state that depletion can make up for technological progress in the industry (Livernois, 1988; Tilton, 2003; Rodriguez and Arias, 2008; Topp et al., 2008). This follows naturally as decreasing reserve levels are likely to increase extraction costs while technical change contributes are likely to decrease extraction costs. In summary, we can assume that technological progress will be offset by increased depletion. The relationship

between the levels of reserves, depletion and extraction costs has been analyzed by others (Zimmerman, 1981; Harris, 1990; Epple and Londregan, 1993, Pickering, 2008).

Future coal prices are very important for future coal production and attempting to accurately project future coal prices is very uncertain. Kavalov and Petreves (2007) link international coal prices to production costs and underline that policies aimed at a further reduction in GHG emissions will generally weaken the position of coal at the expense of nuclear, gas and renewables. Using various scenarios of future coal demand, McCollum and Ogden (2009) studied the US rail network and found that delivered coal prices would not necessarily increase due to required future rail investment.

One must remember that society demands energy, which not necessarily must originate from coal. If the requested energy can be obtained more cheaply from other energy sources, those will be favored in the long run. Höök and Aleklett (2009) point to dramatic changes in the average US coal price while the recoverable reserves have been more or less constant. Following the depletion of the best coal seams in key producing coal beds in the Appalachian Basin, mining became more expensive and complicated, thus reducing its appeal as an energy source. Studies have already highlighted that the remaining coal reserves in the Appalachian basin are located in thinner, deeper coal beds than those currently being mined (Milici, 2000; USGS Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001).

In summary, it is challenging to make good forecasts about future coal prices as they are linked to the development of other energy sources as well. Future energy policies and energy source preferences will be an important factor. In comparison, technological progress seems to be offset by increasing depletion. Finally, 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 decades (Milici and Campbell, 1997).

2.3 Reassessment of coal in the light of future energy policies

The common belief in the continuity of strong economic growth and technological progress of the 1950s and 1960s seems rather inconsistent. Petsch (1982) disapproved of the double digit growth rates commonly used by previous forecasters and points out how the nurtured economic dream of eternal and unending oil supply was torn asunder by the “*First Oil Crisis*” in 1973. Even former technological and economic optimists are now seeing the end of an era with exponential growth (Ayres, 2006). This is hardly surprising, given the underlying arithmetic properties of growth and how quickly unreasonable values are reached for resource production and consumption even for modest growth rates (Bartlett, 1993, 1999, 2004). Arithmetic facts coupled with expected population growth have even been used to show that certain resource policies are “*anti-sustainable*” (Bartlett, 2006).

Regulations can affect coal recoverability both direct, such as prohibitions due to land use conflicts, or indirectly, such as taxation. The Surface Mining Control and Reclamation Act (1977) directly prohibits surface mining in national parks, forests, wildlife refuges, trails, wild and scenic rivers, wilderness and recreation areas. An increasing number of national parks have been established over the years, thus limiting land available for coal production (Figure 1). An additional, 375 776 km² was designated as national wildlife refuges as of 30 September 2007 and 413 km² has been added just for 2007 (US Fish and Wildlife Service, 2007). Physical limitations from land use regulations have generally increased over time.

Petsch (1982) also studied Europe and the Ruhr area and concluded that people have become sensitive to intrusions made on their environment, for instance from mining or colliery

spoil. The Clean Air Mercury Rule (Environmental Protection Agency, 2005) and its overturning in the Court of Appeals have opened up for new policies regarding mercury control, making the future even more uncertain (Höök and Aleklett, 2009). Historically, air quality regulations have shown a strong connection to the demand for low-sulfur coal (Tobin, 1984; O'Brien, 1997). The Clean Air Act Amendments of 1990 (Environmental Protection Agency, 1990), restricting the use of high sulfur coals in power stations, had a significant impact on the demand for high-sulfur coals, mainly from the interior area, and resulted in an increased dependence on low sulfur western coals (O'Brien, 1997). Since then, the Powder River Basin has become the main source of air regulation compliant coal. In addition, the 1987 repeal of the Powerplant and Industrial Fuel Use Act (1978) that had encouraged the use of coal, set the stage for a massive switch to more environmentally friendly natural gas (EIA, 2005).

Figure 1: Historical trend for cumulative national park area in the USA.

Yeager and Baruch (1987) provided a perspective on environmental issues affecting US coal-fired power plants and points out that during 1969-1982 roughly half of all environmental protection investments went towards air pollution control. Public awakening and expanded environmental awareness in the 1960s and 1970s lead to heated debates and stricter regulations. Generally, the Clean Air Act has been an environmental success story although it has done little to mitigate CO₂ emissions (Ackerman et al., 1999).

Obama (2009) stated that “*at a time of such great challenge for America, no single issue is as fundamental to our future as energy*”. Meanwhile, the dependence on imported oil and political pressure to limit greenhouse gas emissions are also influencing future energy policies. Ward (2008) expects the Obama administration to tighten coal regulations and future efforts to tackle climate change and CO₂ emissions. Active CO₂ abatement policies, together with the elimination of grandfathering for SO₂ and NO_x could lead to significant coal plant retirements

(Ackerman et al., 1999). Furthermore, Patiño-Echeverri et al. (2009) showed that the cost of regulatory uncertainty can be significant.

Bang (2010) has discussed the challenges of changing the status quo of US energy policy and some future outlooks. Sustainable development, environmental stewardship and the importance of natural resources for the continued well-being of mankind are driving forces for future policies, at least in the near and medium term. Historical trends point towards increased restrictions and this leads us to assume that future energy policies will not result in significantly increased coal availability, rather the opposite. However, politics are constantly shifting and sudden change cannot be ruled out.

To summarize, we do not expect any major relaxations of restrictions or regulations in the future. Consequently, we assume that present level of restrictions will also be applicable for future outlooks. If increased restrictions are pursued, which we deem to be likely from the political climate, our estimate will be optimistic and the available coal volumes for future production will be even less than what is currently reported in official statistics.

3. Evolution of US recoverable coal reserves

Estimates for coal reserves have been taken from the mineral yearbooks of the U.S. Bureau of Mines (1933-1976) together with various EIA publications and reports, such as Coal Industry Annual (1994-1999) and Annual Coal Report (2001-2007). For reserves of the entire United States, some values have been taken from sources such as World Energy Council (1924-2007), and the German Federal Institute for Geosciences and Natural Resources (BGR, 1980-2007). The historical estimates of recoverable reserves range from 1924 to 2007 for the entire US and from 1950-2007 on a state-by-state basis.

This study has adopted the same area definitions as the EIA (1997) and Höök and Aleklett (2009), as displayed in Figure 2. The Appalachian area is an important producer and production occurs in Pennsylvania, Eastern Kentucky, Maryland, Ohio, Alabama, Tennessee, Virginia, and West Virginia. The Appalachian area contains nearly all of the U.S. anthracite and more than 40% of all estimated recoverable reserves of bituminous coal (Annual Coal Report, 2007). Furthermore, the largest U.S. reserves of coking coal are located in central Pennsylvania and West Virginia.

The interior area, consisting of Arkansas, Illinois, Indiana, Kansas, Western Kentucky, Louisiana, Mississippi, Missouri, Oklahoma and Texas, produces the smallest volume of coal (Annual Coal Report, 2007). Texas and the Gulf Coast Plain contain vast Cenozoic lignite formations (Ruppert et al., 2002). One major issue with Pennsylvanian coal from this area is its generally high sulfur content of more than 2.5% (EIA, 1989). A more comprehensive overview of the sulfur distribution within the Illinois basin, giving mean sulfur contents of 2.9-3.5% for important coal formations, can be found in Hatch and Affolter (2002). For Illinois, around 20 000 Mt coal, of a total recoverable reserve of 32 000 Mt, is located deep and with a sulfur content of over 2.5% (EIA, 1989). Because of the high sulfur content these coals are, at present, generally replaced by coal from other areas with less sulfur.

The western area, comprising the remaining states, is by far the most productive (Annual Coal Report, 2007). Some bituminous coal is present, but most of the producing reserves are sub-bituminous coal and lignite (USGS Central Region Energy Resources Team, 1999). The low-sulfur content of coal from this region has made them attractive as a replacement for high-sulfur coals (Tobin, 1984). Lower production costs have also been noted as an explanation for the rise of western coals (Ellerman et al., 2000).

Figure 2: *Geographical display of the coal-producing areas of the USA used in this study. Actual coal production originates from coal beds not shown here. Adapted from Höök and Aleklett (2009)*

3.1 Historical trends in U.S. recoverable coal reserves

Land use restrictions, property rights, technical confines, economic constraints and similar factors limit the percentage of the reserve base that is available for production. Currently, the EIA estimates this percentage to be 50% (Annual Coal Report, 2007), but in 1997, 54% of the total national DRB was deemed as recoverable (EIA, 1997). The recoverable coal reserves have changed dramatically over time and, generally, a downward trend can be seen (Table 1).

The confusion surrounding reserves and mineable coal has been highlighted by van Rensburg (1975) who reports mineable amounts of US coal that range from 20 to 380 Gt. Van Rensburg (1982) later accounts this discrepancy to a combination of incomplete data, geological variations, and generalizations of mining methods. Previous inability to include availability, mining losses, environmental concerns, technical restrictions and other factors have also been highlighted as an explanation for overestimate reserve figures (Rohrbacher et al., 1993).

For example, the National Academy of Sciences (1978) report that much of the vast lignite formations of North Dakota were unsuitable for underground mining and that imposed restrictions in mining practices were the main obstacle for development. In addition, Höök and Aleklett (2009) identified local resistance against coal mining and conflicts with agriculture important factors behind the severe reduction of North Dakota's recoverable coal volumes.

Table 1: *Estimated recoverable reserves state by state for the United States in Mt. Many states show large downward revisions since 1950, most notably North Dakota and Colorado. The reserves for Kentucky include both eastern and western parts. Pennsylvania includes all coal reserves, i.e. both anthracite and bituminous coal. Source: Höök and Aleklett (2009)*

State	Recoverable reserves 1950	Recoverable reserves 1960	Recoverable reserves 1970	Estimated recoverable reserves 1987	Estimated recoverable reserves 1995	Estimated recoverable reserves 2006
Alabama	29,086	5,764	6,096	2,825	2,738	2,510
Alaska	NA	42,924	59,005	2,457	2,421	2,569
Arkansas	697	1,100	1,097	170	207	207
Colorado	143,532	36,638	36,596	9,517	9,159	8,824
Georgia	412	34	8	NA	2	2
Illinois	75,133	59,139	63,191	32,105	30,816	34,453
Indiana	21,356	15,867	15,723	4,610	3,927	3,653
Iowa	12,916	12,903	2,955	1,132	1,022	1,022
Kansas	7,962	9,411	8,971	606	620	617
Kentucky	54,169	30,402	29,633	14,356	14,749	13,413
Maryland	3,412	539	533	435	374	323
Michigan	99	93	93	NA	54	54
Missouri	35,764	30,294	10,587	3,527	3,494	3,489
Montana	100,330	100,564	100,560	64,935	68,391	67,949
New Mexico	36,045	30,602	27,877	2,836	7,452	6,319
North Carolina	49	50	50	NA	5	5
North Dakota	272,092	159,082	159,053	6,780	6,553	6,239
Ohio	46,749	19,143	18,858	9,629	10,630	10,402
Oklahoma	24,790	1,504	1,492	830	740	724
Oregon	NA	88	19	NA	8	8
Pennsylvania	33,217	32,151	31,512	11,167	11,358	10,602
South Dakota	280	921	922	251	251	251
Tennessee	11,346	862	1,187	475	445	414
Texas	14,004	6,749	4,950	9,991	9,124	8,609
Utah	42,158	11,993	14,616	3,146	2,722	2,449
Virginia	9,295	4,848	4,458	1,459	1,236	712
Washington	28,845	28,759	2,804	734	661	618
West Virginia	50,193	47,128	45,882	19,156	17,825	16,161
Wyoming	54,806	57,493	54,742	39,306	41,189	36,418
Other states	7,417	2,091	2,141	533	315	283
U.S.A. Total	1,116,153	749,137	705,610	242,966	248,488	239,297

The Kaiparowits Plateau in southern Utah, estimated to contain 57 Gt of coal resources (Hettinger et al., 1996; USGS Central Region Energy Resources Team, 2000), is another example of how large coal amounts have been made unavailable by restrictions. Conflicts began in 1965 when Southern California Edison Company proposed a 5000 MW coal-fired power plant, fed with local coal (Powell, 1994). First the project was hailed as an economic boon for the under-developed region, but soon financial and other problems arose and environmental resistance surged (National Academy of Sciences, 1977). In 1975, the project was abandoned after on-going battles with the Bureau of Land Management over environmental safeguards.

Controversies surrounding the Kaiparowits Plateau continued with new coal mining proposals. Andalex Resources Inc. proposed a new coal mine in 1991 much smaller than the suggested projects from 1960s but environmentalists still opposed the idea. Heated arguments and legal battles were finally resolved in September 1996, when President Clinton proclaimed 1.7 million acres as the Grand Staircase-Escalante National Monument using the Antiquities Act of 1906 that authorizes the president to single-handedly designate any federal public lands as national monuments (Bishop, 1996; Nie, 1999; Raffensperger, 2008). Andalex soon declared that the monument had made their project unfeasible and it seems unlikely that it will be pursued (Wilkinson, 2004). More recently, a Utah coal plant permit was blocked by the Environmental Protection Agency's appeals panel due to failure to order limits on CO₂ emissions (Hebert, 2008).

National Coal Council (1987) expressed concerns regarding overstatements of available coal reserves. This was recently echoed by U.S. National Academies (2007) and they also recommended that USGS undertake a new assessment of domestic coal reserves and resources. National Petroleum Council (2007) even claimed that the foundation (Averitt, 1975; USGS 1976) for assessment of American coal supply is too old and implies that a more modern assessment is needed to create a reliable estimate of the future coal supply. Suitably, the USGS has performed more coal availability studies, with comprehensive analyses of all factors that affect recoverability. Some examples are Rohrbacher et al (1993), Watson et al (2001), USGS Northern and Central Appalachian Basin Coal Regions Assessment Team (2001) and Luppens et al. (2008). More analogous studies are recommended for providing reasonable estimates of the coal amounts that actually can be produced in the future and affect energy supply.

4. Modeling future production

The finiteness of coal is caused by the slow creation process compared to the fast extraction process. Coal requires many millions of years to be formed while the extraction process takes only a tiny fraction of that time. If extraction of a resource is faster than replenishment rate, the resource will be "*finite*" and will be eventually exhausted. Future coal production is limited by the geological in-situ amounts available.

The French mathematician Verhulst (1838) reasoned that any population subject to growth would ultimately reach a saturation level (usually described as the carrying capacity) and as a characteristic of the environment, that forms a numerical upper bound on the growth process. Similar reasoning has been expressed by many other scientists in disparate fields and disciplines. This gave birth to the logistic model and a multitude of similar or extended models, all capable of describing the bounded growth phenomena (Tsoularis and Wallace, 2002).

Residing on the same basic ideas of natural limits, Hubbert (1956) proposed a production model for finite resources, assuming that production levels begin 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. Höök and Aleklett (2009), and the references their work contains, present a detailed synopsis of this methodology and its theoretical framework.

Hubbert (1959) used the symmetric logistic function as a tool for creating outlooks. The logistic function is given by the differential equation

$$\frac{dQ}{dt} = bQ \left(1 - \frac{Q}{URR} \right) \quad (2)$$

where URR is the ultimately recoverable resources of any finite energy resource, Q denotes the cumulative production, and dQ/dt is the rate of extraction. The constant b governs the growth rate. Physically, one may interpret the logistic equation as a rate of extraction that will initially increase exponentially because the ultimate limit to production is unimportant due to the fact that extracted volumes represent only a small part of the URR. As cumulative production grows and becomes a significant share of the URR, extraction becomes more difficult and the rate of extraction decreases and this may also be seen as a representation of the challenges imposed by depletion. Since there is an ultimate limit to extractable amounts, production will finally go to zero. The solution to the logistic equation obtains cumulative production as a function of time and is mathematically expressed by

$$Q(t) = \frac{URR}{\left(1 + \frac{URR - Q(0)}{Q(0)} \right) \exp(-kt)} = \frac{URR}{(1 + a * \exp(-kt))} \quad (3)$$

Many other mathematical curves can also be used to create future outlooks within this theoretical framework, where future production is ultimately bound. This forecasting methodology has proved to be applicable to many resources other than fossil fuels. For instance, whales and their blubber oil were on the verge of becoming extinct/exhausted, despite their “renewable” nature, prior to the utilization of crude oil and the case of 19th century whaling is an excellent illustration of a complete Hubbert cycle, where a resource has been extracted at a much faster rate than it could be reformed (Bardi and Yaxley, 2005, Bardi 2007). Petroleum, uranium and many other resources have also been modeled using this methodology.

Bardi (2005) showed that mineral production always results in a bell shaped curve except for very special assumptions, but the shape was not necessarily symmetric. Logistic curves and Hubbert curves are symmetric, but there are many other curves that are asymmetric. Moore (1966) and Fitzpatrick et al. (1973) used asymmetric Gompertz curves for analyzing and projecting historic supply patterns of oil and other exhaustible natural resources. Likewise, the asymmetric HCZ-model (Hu et al., 1995) has been used for petroleum forecasts in China (Feng et al., 2008). Figure 3 and 4 give some examples of how simple mathematical curves can be used for resource constrained modelling and how the outlook is dependent on the chosen curve.

Van Rensburg (1975) discussed various mathematical curves, such as Gauss or logistic curves, and concluded that they can serve as a tool for resource management – in order to determine what might happen to future production if availability represents a major constraint. To a certain degree this is true, but they do not include constraints other than availability, and for this reason need to be used in combination with economic and policy analysis to obtain a holistic picture.

Figure 3: Logistic curves applied to coal production in Pennsylvania and constrained by the recoverable reserves and demonstrated reserve base estimated given by the EIA. Adapted from: Höök and Aleklett (2009)

Figure 4: Gompertz curves applied to coal production in Pennsylvania and constrained by recoverable reserves or demonstrated reserve base estimates given by the EIA. This asymmetric curve gives a different outlook, despite the fact that it is limited by the same recoverable amounts as the logistic curve.

Modis and Debecker (1992) have showed that instabilities associated with production can result in chaos-like states before and after growth and give several examples of this in industrial production time series for coal and cars. More recently, Modis (2007) has written an excellent and amusing overview of the strengths and weaknesses of S-curves and concluded that the forecaster's ultimate test is the accuracy of the forecast, not the easiness or elegance of the method used.

Hubbert (1956, 1959) was an early pioneer in proposing mathematical models capable of describing production where available resources places a major constraint on future production. Since then, there have been many other researchers who have developing various modelling approaches. For example, Mohr and Evans (2009) have developed a coal forecasting model based on real world mineral exploitation, resulting in an asymmetric bell shaped production forecast, which for most cases produces the same results as for simple growth curves. Also, Jakobsson et al. (2009) have defended resource constrained modelling and concluded that it is the only plausible tool for long term outlooks.

4.1 Depletion rate investigations

Depletion rate of remaining reserves has shown to be a vital parameter in crude oil production and can be used for understanding future production (Höök et al., 2009; Höök, 2009; Jakobsson et al., 2009). This thinking can also be applied to coal production. The remaining reserves are defined as follows:

$$R_r = R_0 - Q_t \quad (4)$$

Where R_r = remaining reserves, R_0 = originally present reserves or ultimate reserves and Q_t = cumulative production up to time t . From this, one can now define the depletion rate of remaining reserves ($d_{\delta t}$) as follows:

$$d_{\delta t} = \frac{q_t}{R_r} = \frac{q_t}{R_0 - Q_t} = \frac{1}{RPR_n} \quad (5)$$

Where RPR_n = reserve-to-production ratio. In fact, depletion rate of remaining reserve is the reciprocal of the R/P ratio. This measure simply shows the percentage of the remaining reserves that are extracted at a given time.

For oil fields, a maximum $d_{\delta t}$ value occurs prior to the onset of decline and this parameter is more or less constant (Höök et al., 2009; Höök, 2009). At this point, the depletion-driven decline, primarily caused by decreasing reservoir pressure or water influx, begins to dominate over other production factors. While coal production is physically different to oil production, there is still an analogy since coal production will become increasingly challenging as the easily recoverable material gets extracted leaving behind the challenging reserves (Dasgupta and Heal, 1979). This is evidenced with the declining trend in calorific value of US coals (Höök and Aleklett, 2009). Consequently, the declining production of old mines will at some point be impossible to offset with new mines and the onset of decline for the entire region is reached.

How much coal can one realistically produce annually from the recoverable reserves? The extensive history of coal production in the USA allows for an empirical investigation of this question. Based on the historical trends in recoverable reserve estimates, we can assume that the

presently reported recoverable reserves are a reasonable proxy for the remaining reserves. Historical cumulative production data is taken from Milici (1997) and the EIA. Combining these two sources of information, one can obtain a plausible estimate for the ultimate reserves.

Many of important coal producing states have passed their peaks and have been in a stage of declining production for quite some time. Many coal regions in the United States are mature, with the largest and most promising formations already discovered, assessed and developed (Milici, 1996). This is particularly true for Appalachian Basin which in recent years has experienced increasing production costs due to depletion and difficulties in keeping up with demand (Milici and Campbell, 1997; Milici, 2000). A compilation of the $d_{\delta t}$ values for selected states can be seen in Table 2. Generally, the peak seems to have occurred when only around 1% of the remaining reserves were extracted annually.

High depletion rates of roughly 3% can only be found in relatively small regions such as Pennsylvania anthracite. The $d_{\delta t}$ limitation implies that a large production level must be accompanied with equally large reserves and that only a fraction of the remaining reserves can be produced annually. This results in declining production levels as the coal reserves get more and more depleted, which ideally leads to lingering production profiles trending towards zero as times goes to infinity.

As of 2008, only two US states (Missouri and Virginia) were producing more than 2% of their remaining reserves. Depletion rates for all the remaining states have varied from 0-2% with the majority below 1%. $d_{\delta t}$ Currently, the $d_{\delta t}$ values for the dominating coal producing states of Wyoming and West Virginia are at 0.9% and 1.16% although they have not peaked yet. However, Wyoming and West Virginia is nearing $d_{\delta t}$ values where other states have peaked. Just as for crude oil (Höök, 2009), we found that $d_{\delta t}$ generally decreases after peaking even though it can remain more or less constant too (Figure 5).

Table 2. *Depletion rate of remaining reserves for selected coal producing states.*

State	Ultimate reserves [Gt]	Peak year	Peak prod. [Mt]	Prod. in 2008 [Mt]	Depletion rate at peak [%]
Pennsylvania	26	1918	251.6	59.2	1.2
<i>PA anthracite</i>	6	<i>1918</i>	89.7	<i>1.54</i>	2.8
Kentucky Total	22	1990	157.2	108.8	1.0
<i>East Kentucky</i>	<i>11</i>	<i>1990</i>	<i>116.5</i>	<i>81.5</i>	<i>1.7</i>
<i>West Kentucky</i>	<i>11</i>	<i>1975</i>	<i>50.5</i>	<i>27.2</i>	<i>0.5</i>
Ohio	14	1970	50.0	23.8	0.4
Virginia	3	1990	42.5	22.3	3.3
Illinois	40	1918	81.0	29.9	0.2
Texas	10	1990	50.6	35.4	0.5

Figure 5. *Depletion rate behavior of selected regions.*

In addition, $d_{\delta t}$ can be used as a constraint for future production as maximum depletion rate modeling dictates that there exists a limit for the amounts that can be produced from the reserves (Jakobsson et al., 2009). Table 2 and Figure 5 give some examples of typical depletion rate behaviors and some maximum $d_{\delta t}$ values derived from historical data. Applying such constraint to the curve fitting can rule out certain outlooks that are mathematically sound, but rely on unreasonable depletion rates.

Historical anthracite production of Pennsylvania follows a logistic behavior very well and likewise its remaining production may be assumed to continue the logistic behavior, but a good fit can easily end up with unreasonably high future $d_{\delta t}$ values (Figure 6). Theoretically it is possible to deplete the remaining anthracite reserves very fast, but if production is assumed to follow a similar pattern as in history one cannot regard this outlook as reasonable.

In comparison, applying a constraint to the depletion rate causes a very different outlook (Figure 7). Even if the remaining reserves are depleted equally fast as in the 1920s, the future production will be more modest and stretched out compared to Figure 6. Any short term rapid increases must be accompanied with rapid depletion of remaining reserves, much higher than anything seen before in history.

Figure 6. *Pennsylvania anthracite production fitted with logistic curves. Although mathematically feasible, this outlook implies that the remaining anthracite will be depleted roughly 4 times faster than anything seen in history.*

Figure 7. *Pennsylvania anthracite production fitted with logistic curves and constrained by a maximum depletion rate of 4%. Even this modest production increase requires a massive increase of the depletion rate.*

5. Future production outlooks

Two different mathematical curve models have been used for creating future production outlooks. Höök and Aleklett (2009) utilized a sum of two logistic curves, limited by either recoverable or demonstrated reserves, to produce long term projections for future US coal production. It was concluded that using the demonstrated reserve base gives an extremely unrealistic picture, as it implies that all restrictions are ignored.

The need to include surface and sub-surface land-use and restrictions in determining coal production figures is of great importance. Such factors are critical and can have enormous influence over actual production. For instance, Ruppert et al. (2002) have shown that less than one-half of the total available coal resources in parts of the Appalachian Basin were available for mining and only one-tenth were considered economically recoverable. Luppens et al. (2008) reached a similar conclusion for the Gillette coal field in Powder River Basin.

The historical production of all US coal producing states were fitted with Gompertz curves and constrained exactly as in Höök and Aleklett (2009). The asymmetric Gompertz curve produces a gentler decline after the peaking than the logistic curve, although the peak arrives sooner (Figure 8). For comparison, the logistic outlooks presented by Höök and Aleklett (2009) are also shown in Figure 9. In both cases, the largest reserve holders will be dominating future US coal production.

Figure 8. Possible future production based on Gompertz curves. The Appalachian basin and the interior area can roughly maintain present production levels until 2100, but the future production is governed by the western area.

Figure 9. Possible future production based on logistic curves. Also in this case, the future shape is governed by production from the western area, in particular Wyoming and Montana. Adapted from Höök and Aleklett (2009)

For example, one can study what might happen if political decisions prohibited large amounts of coal from being recovered or if hindering restrictions were removed. If Montana prohibited the further development of its coal reserves and froze its production level at around 40 Mt annually, US coal production and CO₂ emissions from coal combustion could peak within a few decades at most (Figure 10). Likewise would removal of recoverable coal amounts in Illinois and other large reserve holders greatly reduce future US coal production capability, which could be motivated by climate change mitigation policies. Restricting coal resources could be a cheap way of preventing future emissions.

In summary, only a few states hold major recoverable coal volumes and they will have the largest impact on future coal production. Consequently, future trends in regulations and production for these states will matter enormously for future supply outlooks.

Figure 10. Same outlook as in Figure 8, but without any further development of Montana's vast coal reserves.

6. Conclusions

Crustal abundance of coal or resource estimates are very poor indicators of the amounts that can be realistically produced in the future. Production is dependent on availability, technology and economical restrictions which will severely reduce the coal amounts that can be recovered in practice. Future energy policies will also have a major role on future coal utilization. Future coal production is dependent on many more things than just the coal in place amounts. Historical trends in US recoverable coal assessments indicate that imposed regulations will continue to strongly influence coal production levels. Consequently, current reported reserves may not be fully realizable into the future. Updated and improved assessments with more focus on the coal amounts that are realistically available for future production should be encouraged.

Future production can be modeled in many ways, but for long term outlooks it is only resource-constrained models that are reasonable (Jakobsson et al, 2009). Using Gompertz curves, a production peak occurs in 2050 followed by a gentle decline. In comparison, the logistic outlook projects a stable production until 2100 but will contain a more rapid decline phase once the onset of decline is reached. In both cases, Wyoming and Montana will be the key players in the future US coal production. Höök and Aleklett (2009) discussed some of the challenges facing Montana, but unless their vast reserves are developed, USA coal production could reach its maximum much earlier than 2050. If stricter regulations are imposed, for instance CO₂ taxes or direct restrictions against coal mining, the projections reported in this study will be optimistic.

Additionally, depletion rates can be used to constrain modeling even more, as there are empirical indications that certain depletion rates cannot be surpassed without reaching a production peak. Empirical data indicates that only a few percents of the recoverable reserves can be produced annually.

The forecasting methodology presented here can also provide a convenient tool for resource management in order to determine what may happen if availability becomes a predicament (van Rensburg, 1975). This may be used to study energy policy implications in the long run.

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