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Potential for Coal-to-Liquids Conversion in the U.S.-Resource Base

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By applying the multi-Hubbert curve analysis to coal production in the United States, we demonstrate that anthracite production can be modeled with a single Hubbert curve that extends to the practical end of commercial production of this highest-rank coal. The production of bituminous coal from existing mines is about 80% complete and can be carried out at the current rate for the next 20 years. The production of subbituminous coal from existing mines can be carried out at the current rate for 40–45 years. Significant new investment to extend the existing mines and build new ones would have to commence in 2009 to sustain the current rate of coal production, 1 billion tons per year, in 2029. In view of the existing data, we conclude that there is no spare coal production capacity of the size required for massive coal conversion to liquid transportation fuels. Our analysis is independent of other factors that will prevent large-scale coal liquefaction projects: the inefficiency of the process and either emissions of greenhouse gases or energy cost of sequestration.

KEY WORDS: Hubbert curve, production, history, reserves, coal ranks.

INTRODUCTION

There is a popular belief that coal production in the United States may continue practically forever at the current rate of about 1 billion tons per year. For example, a U.S. coal industry website states the following facts about coal:

> The United States has enormous coal "resources" and "recoverable reserves[4]." The most reliable information about coal is published by the Energy Information Administration (EIA). The most recent figures available from the EIA, show that America's estimated recoverable reserves of coal stand at 275 billion tons, an amount that is greater than [those for] any other nation in the world. These recoverable reserves [are] capable of meeting domestic demand for more than 250 years at current rates of consumption.[5]

While this statement may be true in principle, our analysis of historical coal production data shows that the existing U.S. mines can continue producing bituminous coal at the current rate for the next 20 years and subbituminous coal for about 20 years more. To extend the next four decades of coal production at today's rate to over 250 years will require the costly and environmentally unacceptable expansions of existing mines and the opening of new mines that will operate at ever greater depths in ever thinner coal seams.

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[4] Defined in the next section.

[5] About Coal, America's most abundant energy resource and a source of chemicals, fertilizer, and power worldwide, www.clean-energy.us/facts/coal.htm.

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The goal of this paper is to characterize the near-future of coal production in the United States and demonstrate that there is no large spare production capacity that could be used to create mega-scale conversion of coal to liquid transportation fuels. In a separate paper, we will investigate what would it take to carry on such a conversion in the only theoretically possible location in the United States, southeastern Montana.

Here, we first characterize the coal resource base in the United States, and then perform a multi-Hubbert curve analysis of anthracite, bituminous, and all coal production in the United States.

COAL RESOURCES

U.S. coal resources are generally regarded as very large, which is the premise for the development of large-scale coal-to-liquids (CTL) conversion. The size and distribution of these resources bears examination. The United States has three major coal-producing areas: the Appalachian Basin, the Illinois Basin, and the Rocky Mountain area. Figure 1 shows the major coal-producing regions of the United States and Figure 2 zooms on the Powder River Basin (Flores and Bader, 1999). Coal reserves reported by the U.S. Geological Survey are based on seam thickness and depth, and do not necessarily represent economic reserves (Fettweiss, 1979).

Coal Reserves

There are three categories of coal reserves reported by the EIA: demonstrated reserve base, estimated recoverable reserves, and recoverable reserves at producing mines. Table 1 shows these categories for selected coal-producing states. As one can see, the relationship between reserves and production is not clear. The broader reserve categories put the most coal in Montana, Illinois, and Wyoming, but the producing mines category reflects Wyoming's dominant position in coal production. Coal reserves are not comparable with oil reserves, except that the category of recoverable reserves at producing coal mines is approximately equivalent to proved developed oil reserves.

Coal production trends tell a simpler story; production is declining in the Appalachian and Illinois Basins, and is increasing in Wyoming and Colorado. Elsewhere in the Rocky Mountain area, production is about constant. Tables 2 and 3 show the states with the largest 10-year coal production increases and decreases. Huge growth in Wyoming

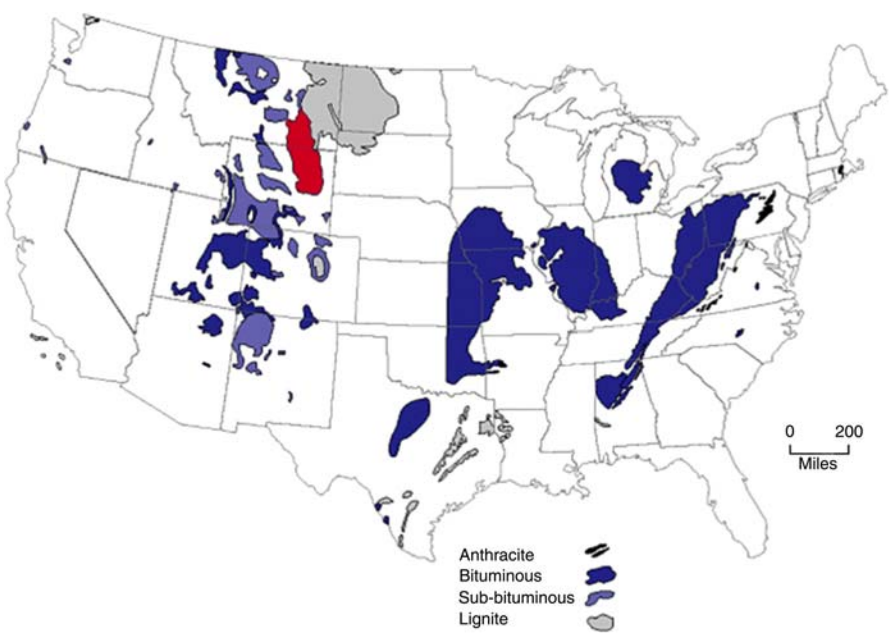

Figure 1. Map of coal-producing regions of the United States. The Powder River Basin is shown in red. *Source*: EIA.

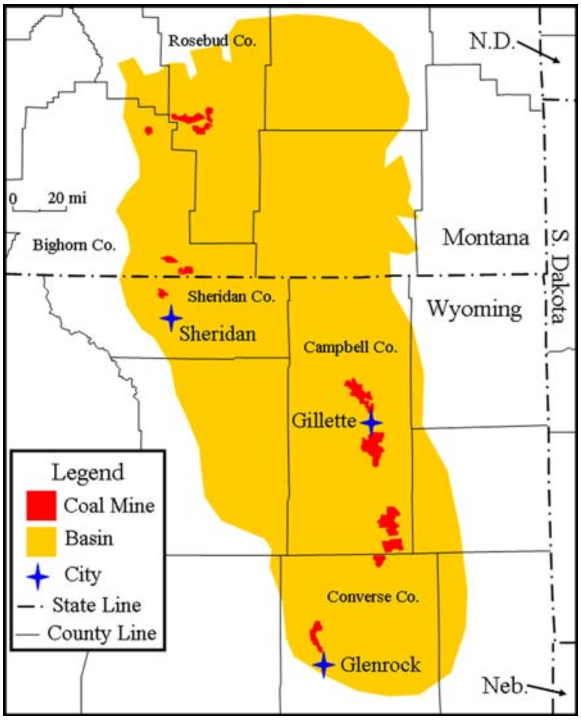

Figure 2. Map of the Powder River Basin with mines shown in red. Adapted from Flores and Bader (1999).

Table 1. Coal Reserves and Production, Selected States

State	Recoverable Reserves (million short tons)	Mine Reserves (million short tons)	2007 Production (million short tons)
Montana	74,856	1251	43.4
Wyoming	39,674	7330	453.6
Illinois	37,957	1286	32.4
West Virginia	17,669	1828	153.5
Kentucky	14,682	1182	115.3

coal production comes from surface mining of subbituminous coal in Campbell and Converse Counties in the Powder River Basin. Coal production in Colorado is mostly underground mining of bituminous coal west of the Continental Divide, in the Colorado River watershed.

Coal Classification

Coal is classified by rank, going from anthracite (highest) to lignite (lowest). In the United States, anthracite and bituminous coal are mostly produced from underground mines, while subbituminous coal

Table 2. States with Greatest Coal Production Increases, 1997–2007

State	Production Increase 1997–2007 (thousand short tons)
Wyoming	171687
Colorado	8935
Montana	2385
Arkansas	65
Kansas	60

Table 3. States with Greatest Coal Production Decreases, 1997–2007

State	Production Decrease 1997–2007 (thousand short tons)
Kentucky	−40573
West Virginia	−20263
Texas	−11380
Pennsylvania	−11150
Virginia	−10491
Illinois	−8714

and lignite are produced almost exclusively from surface mines. U.S. coal production shows a clear trend of declining production of high-rank coals and rapidly increasing production of subbituminous coal, the second-lowest rank. Lignite resources in North Dakota and Montana are large, but air quality and other environmental and technological considerations have limited the use of lignite. Figure 3 shows historical U.S. coal production by rank.

Another way of classifying coal is sulfur content. The Wyoming, Montana, and Colorado coals are lower in sulfur than those of comparable rank from east of the Mississippi River (Anonymous, 1999). This has been an important factor in the development of western coal in recent years because power plants have been under pressure to reduce their emissions of sulfur oxides.

Yet another way of classifying coal is by heat yield. This classification is similar to rank, with anthracite higher than bituminous coal, which is higher than subbituminous, which is higher than lignite. The difference is that large ranges of values are found within the bituminous and subbituminous categories, and there is some overlap. By this classification, the Wyoming and Montana coals are at the low end of the subbituminous range with heat yields of about 8200 btu per pound (19 MJ kg^{-1}). By comparison, anthracite yields up to 15000 btu per pound (35 MJ kg^{-1}). The 1997 EIA coal reserves review lists reserves by state, divided into heat yield and sulfur content ranges (Anonymous, 1999).

Major Coal Mines

Concentrated resources are desirable for CTL conversion because the plants have significant economics of scale. The 13 largest coal mines in the United States are listed in Table 4. This provides a perspective on the location and relative size of the most concentrated resources. Twelve of the thirteen largest coal mines in the United States are located in the Powder River Basin.

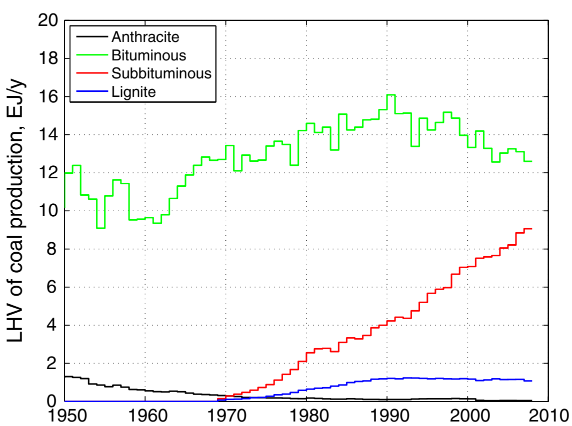

Figure 3. Historical coal production in the United States by rank. Note that currently the United States uses around 110 exajoules (EJ) of primary energy per year (Patzek, 2008). *Source*: EIA.

Table 4. Thirteen Largest Coal Mines in the United States

Mine	State	2007 Production (short tons)
North Antelope Rochelle	Wyoming	91,523,280
Black Thunder	Wyoming	86,196,275
Cordero	Wyoming	40,467,627
Jacob's Ranch	Wyoming	38,101,560
Antelope	Wyoming	34,474,682
Caballo	Wyoming	31,172,396
Belle Ayr	Wyoming	26,608,765
Buckskin	Wyoming	25,268,145
Eagle Butte	Wyoming	24,985,991
Rawhide	Wyoming	17,144,361
Spring Creek	Montana	15,712,091
Freedom	North Dakota	14,955,989
Rosebud	Montana	12,583,084

Based on the above assessments, the most attractive area for CTL conversion is the Powder River Basin of Wyoming and Montana; it contains 12 of the 13 largest coal mines in the United States and large undeveloped resources remain. A key issue there is insufficient availability of water.

Bituminous coal is mined underground in Colorado and Utah and production has been increasing, but the mines are distributed over a vast area and there is no surplus water in the Colorado River watershed. Although large coal reserves are attributed to Illinois and water is abundant there, coal production in Illinois has been steadily declining for at least 15 years, partly because Illinois coal is high in sulfur content. During that time, coal production from the Powder River Basin has grown more than that of the United States as a whole. One reason for this growth is that the very large surface mines that characterize coal production in the Powder River Basin have low labor costs. The EIA lists labor productivity in Wyoming surface mines in 2007 as 34.19 short tons per employee-hour. By comparison, underground mines in the Appalachian Basin average 2.91 short tons per employee-hour (Anonymous, 2008a), nearly 12 times less.

The Powder River Basin coals are found in the Tongue River member of the Fort Union Formation of Paleocene age. The depositional environment was a warm subtropical wooded swamp, similar to parts of southern Louisiana today. This was a very large swamp, and the Wyodak-Anderson Coal was deposited as a laterally continuous unit over most of the basin. Clastic sediment input was overbank and crevasse-splay mudstone deposits associated with major floods.

The unique feature of this swamp was the combination of limited clastic sediment input with high biologic productivity; the Powder River Basin is known for unusually thick coal seams. In the central part of the Powder River Basin, the seams that make up the Wyodak-Anderson Coal merge into a single bed that ranges from 46 to 202 ft (15–62 m) in thickness and is present over 950 square miles (2500 km^2) of the Powder River Basin in Wyoming and southernmost Montana (Flores and Bader, 1999). This merged seam is at a depth of more than 1000 ft (300 m), so it is considered underground mineable reserves.

The Rosebud and Knobloch Coals are present on the Montana side of the basin and extend north of the Wyodak-Anderson. Each of these units can be a single massive coal or may be divided into multiple separate coal beds, complicating nomenclature. The Wyodak-Anderson Coal is at its thickest in eastern Johnson County, Wyoming, in the central part of the Powder River Basin, but there are no coal mines in Johnson County because the overburden is too thick for surface mining. The Wyodak-Anderson Coal is subbituminous and has a fairly low heat yield, but it also has a lower-than-average sulfur content of about half a pound of sulfur per million btu (200 mg S/MJ). Table 5 gives mean compositional values for coals from current and proposed mines in the Powder River Basin.

The sediments on the eastern flank of the Powder River Basin dip 2–5°, so the region of surface-mineable coal is a narrow strip in Campbell and Converse counties in Wyoming. The Montana side has lower dips and multiple coals, so surface-mineable coal exists over a broad area in Bighorn, Rosebud, Powder River, and Custer Counties. Except for the Rosebud Coal in one area, the other coals are not as thick as the Wyodak-Anderson, which is mostly in Bighorn County. The Wyoming side of the Powder River Basin has thicker coal seams and better rail access, so it has been developed more.

Coal development in Montana is characterized by a few large surface mines that have been in existence for some time. These mines are located on the thickest part of the Wyodak-Anderson and Rosebud coals. Although Montana has been described for decades as having the largest coal reserves in the United States, its coal production has been relatively static for the past 15 years. In Wyoming, coal production has grown dramatically during the same time period. These different patterns of mine development in Wyoming and Montana have been driven by the economics of surface mining; it is easier to mine one or two massive coals than three or more thinner ones. Figure 4 shows a mine in the Wyodak-Anderson Coal in southernmost Montana.

Clinker beds are present over large parts of the Powder River Basin. These have been caused by lightning strikes igniting exposed coal seams. Coal seam fires have substantially reduced the surface-mineable coal reserves of the Powder River Basin, especially on the Montana side of the Wyodak-Anderson coal. Surface coal mines are located between the clinker areas. The clinker beds

Table 5. Mean Composition of Powder River Basin Coal (Stricker and Ellis, 1999)

Ash content (wt.%)	6.44
Moisture content (wt.%)	27.66
Sulfur content (wt.%)	0.48
Heating value (Btu/lb)	8220
Heating value (MJ/kg)	19.1

Figure 4. Decker Coal Mine, Montana, showing split Wyodak-Anderson Coal. Image from Flores and Bader (1999).

themselves are nodular and resemble terra cotta. The clinker beds do not persist to great depths, so much more of the Wyodak-Anderson Coal remains in deeper areas, many of which are too deep for surface mining. At present there is no underground mining of coal in the Powder River Basin.

Lignite

Lignite deserves a separate discussion. Lignite is the softest coal and is sometimes considered a separate category rather than a type of coal. Because of its high content of ash and sulfur, and its low heat yield, lignite has not been mined on a large scale for power plant fuel in the United States. The history of U.S. lignite production is not suitable for Hubbert analysis because it is dominated by a small number of projects, many of which were created with government financing. The largest U.S. lignite mine produces at a nearly constant rate to feed a coal gasification facility in North Dakota. Lignite accounted for 7.2% of U.S. coal production in 2006 and 8.7% of the United States demonstrated reserve base in the 1997 reserve study. Lignite is produced in Texas, North Dakota, Louisiana, and Mississippi. To give an idea of the difficulty in analyzing lignite production history, the state with the largest demonstrated reserve base of lignite is Montana, yet it had no production in 2006.

The most important lignite deposits in the United States, accounting for 62% of 2007 lignite production, are found in Eocene-age sediments in the Gulf Coast area, especially the Wilcox Formation. An analysis of 52 samples of Wilcox Formation lignite by the Arkansas Geological Survey found average values of 35.7% moisture, 17.6% ash, 0.57% sulfur, and 5759 Btu per pound (12.0 MJ/kg or 1/3 of the heating value of anthracite) on an as-received basis (Prior, Clardy, and Baber, 1999).

Lignite has more hydrogen than true coals, which is an advantage for Fischer–Tropsch synthesis, but the ash content presents a waste disposal problem. Because of the difficulty in analyzing the lignite production history, the conclusions of this paper apply to anthracite, bituminous and sub-bituminous coals, but not to lignite. Lignite resources are best evaluated by traditional volumetric methods, which indicate that the demonstrated reserve base of lignite in the entire United States is about a quarter of the reserve base of sub-bituminous coal in the Powder River Basin.

HISTORY OF COAL PRODUCTION IN THE UNITED STATES

The past and future coal production in the United States is modeled here with the multi-Hubbert curve model described in detail in Patzek (2008). The historical coal production data series are from Anonymous (2008b) for the years 1949 through 2007 and from Schurr and Netschert (1960) for the years 1850 through 1948. The annual production data are subdivided by coal rank.

Here it suffices to say that, theoretically, the Hubbert curve approach captures very well coal production from a multitude of independent mines in the United States. For example, a single complete Hubbert curve models anthracite production in the United States (see Fig. 5).

Extending this approach to all anthracite and bituminous coal produced in the United States requires four Hubbert curves: (1) the fundamental Hubbert curve with the peak in 1988; (2) the early production curve with the peak in 1897; (3) the WWI curve with the peak in 1920; and (4) the WWII curve with the peak in 1946 (see Fig. 6). The historical data and the Hubbert curves in Figure 6 can be integrated in time to yield the cumulative coal production (see Fig. 7). The most important conclusion is that the slope of the cumulative production of bituminous coal (anthracite production is already irrelevant) remains comparable to the present one for only 20 more years and some 80% of U.S. bituminous coal has already been produced from the

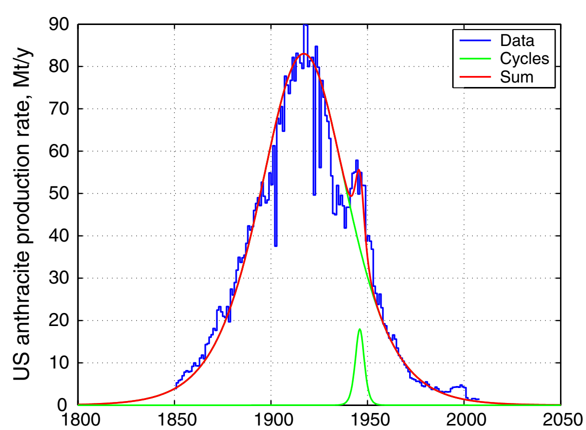

Figure 5. Almost all history of anthracite production in the United States is modeled with one fundamental Hubbert curve. The small second Hubbert curve reflects WWII production. Anthracite production data since 1850 has been obtained from EIA and Schurr and Netschert (1960).

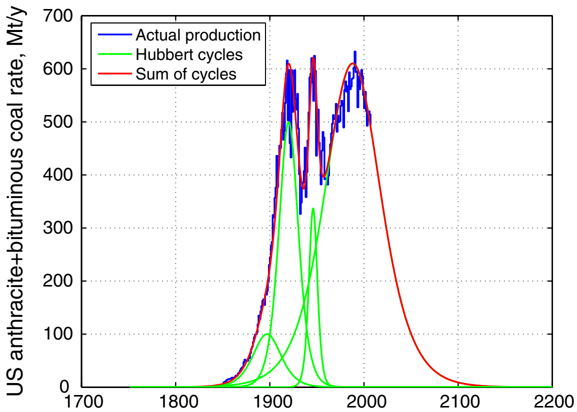

Figure 6. The production rates of anthracite and bituminous coal in the United States since 1850 can be modeled with four Hubbert curves, the fundamental curve and three smaller curves for the pre-1900 coal production, WWI, and WWII. The production data are from EIA and Schurr and Netschert (1960).

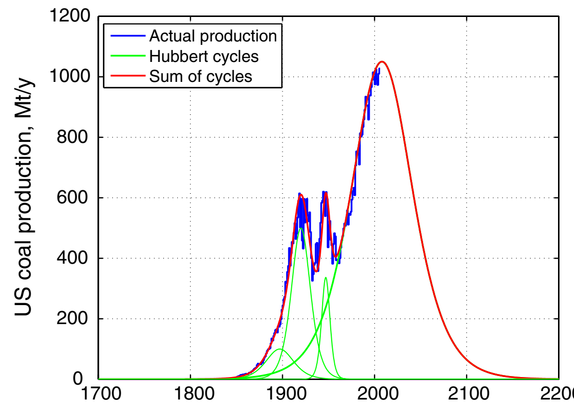

Figure 8. The production rate of coal of all ranks in the United States since 1850 can be modeled with four Hubbert curves, the fundamental curve and three smaller curves for the pre-1900 coal production, WWI, and WWII. The production data are from EIA and Schurr and Netschert (1960).

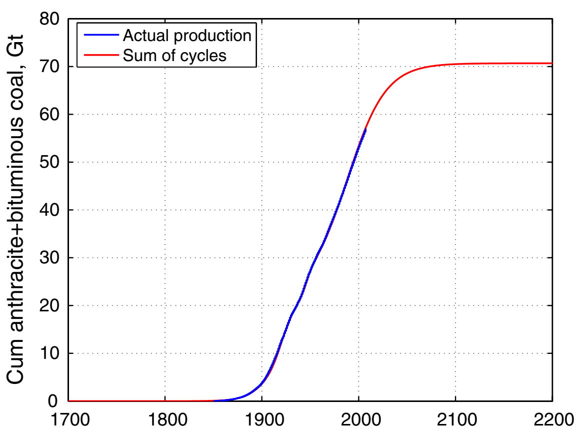

Figure 7. The cumulative production of anthracite and bituminous coal in the United States since 1850 shows that all mines have produced about 80% of their reserves and will be producing bituminous coal at rates comparable to the present one for another 20 years. Anthracite production is already negligible.

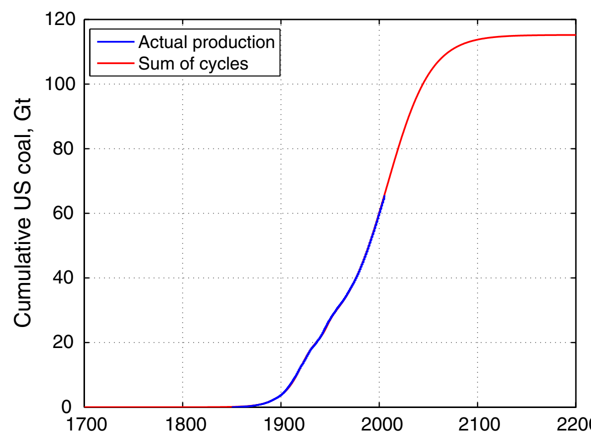

Figure 9. The cumulative production of coal in the United States since 1850 shows that all mines have produced about 55% of their reserves and will be producing mostly subbituminous coal at rates comparable to the present one for another 40 years.

existing mines. This conclusion is consistent with the data in Table 3.

A similar analysis of all coal production in the United States is shown in Figures 8 and 9. The only difference is that the fundamental Hubbert curve now peaks near 2008, because of the inclusion of subbituminous coal. It appears that about 55% of coal producible from historical and current mines has been produced and production can be maintained at rates comparable to present for another 40 years.

The remaining producible coal in Figure 8, equal to roughly 50 billion tons, is much less than the 275 billion tons estimated by the EIA. The reason for the discrepancy is a fundamentally different approach to calculating remaining reserves. The EIA takes all known coal that passes a set of thickness versus depth criteria, applies a recovery factor depending on the type of mining, and produces estimated recoverable reserves. The Hubbert approach is based on actual production history and it reflects economic constraints to a greater extent than a simple thickness versus depth model. Obviously, many of the existing mines can be expanded, but this process is neither instantaneous nor cheap. In many places, environmental impacts and costs will limit future mine expansions. With little or no mine expansion, coal production rate is expected to decrease to below 800 million tons per year after 2035 (see Fig. 8).

CONCLUSIONS

The multi-Hubbert curve model of historical coal production in the United States leads us to the most important conclusion of this paper. Based on the existing coal production data from all mines in the United States, it appears that the current mines will be significantly exhausted 50–60 years from now. New giant mines in the Powder River basin, the only region of the country with a high upside potential for such mines, will have to be developed to replace the falling production, and this new coal may be already subscribed to by the current users, especially power utilities. Thus, talk of a massive diversion of coal to production of liquid transportation fuels is likely to be just that, regardless of other serious environmental and technical reasons for abstaining from such a diversion. Some of these other reasons will be described in a separate paper. Because Wyoming is already the largest U.S. producer of coal, producing roughly 40% of all coal, the new mine extensions will have to be in southeastern Montana. The conclusions of this paper apply to anthracite, bituminous and sub-bituminous coals, but not to lignite, which has little production history in the areas where it is most abundant.

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