CHAPTER 1

Global Reserves of Coal Bed Methane and Prominent Coal Basins

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Abstract

Fossil fuels comprise nearly 90% of the proved reserves of global energy. Coal is the major component of fossil fuel containing nearly 90% of the fossil fuel energy. The growing population of the world would need 5 to $7.5 \times 10^{20}$ J of energy to live well. To meet this growing demand extraction of gas contained in coal has become necessary. The vast deposits of coal (17–30 T tons) contain approximately 30,000 TCF of gas, called coal bed methane (CBM). A brief description of the prominent coal basins with a CBM reserve estimate is provided. The list includes coal basins of United States, Western Canada, United Kingdom, France, Germany, Poland, Czech Republic, Ukraine, Russia, China, Australia, India, and South Africa. These countries produce 90% of global coal production and nearly 100% of all CBM production. Since the economic depth limit for mining is around 3000 ft, only about 1 T ton of coal can be mined leaving a vast reserve of coal full of CBM unutilized. Vertical drilling with hydrofracking (a copy of conventional oil and gas production technique) is the main technique used to extract gas at present. This works only up to 3000–3500 ft depth because of serious loss in permeability. A new technique that has been eminently successful in deep and tight Devonian Shale (Marcellus Shale) is advocated for CBM production from deeper horizons. Lastly the CBM reservoir is compared to conventional reservoirs.

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The disparities are very substantial warranting a new and proper treatment of the subject, “Reservoir and Production Engineering of Coal Bed Methane.”

1.1 INTRODUCTION

Coal seams were formed over millions of years (50–300 million) by the biochemical decay and metamorphic transformation of the original plant material. The process known as “coalification” produces large quantities of by-product gases. The volume of by-product gases (methane and carbon dioxide) increases with the rank of coal and is the highest for anthracite at about 27,000 ft$^3$/t (765 m$^3$/t) of methane [1]. Most of these gases escape to the atmosphere during the coalification process, but a small fraction is retained in coal. The amount of gas retained in the coal depends on a number of factors, such as the rank of coal, the depth of burial, the immediate roof and floor, geological anomalies, tectonic forces, and the temperature prevailing during the coalification process. In general, the higher the rank of coal and the greater the depth of coal, the higher is the coal’s gas content. Actual gas contents of various coal seams to mineable depths of 4000 ft (1200 m) indicate a range of 35–875 ft$^3$/t (1–25 m$^3$/t).

Methane is the major component of coal bed methane (CBM), accounting for 80–95%. The balance is made up of ethane, propane, butane, carbon dioxide, hydrogen, oxygen, and argon. Coal seams are, therefore, both the source and reservoir for CBM.

1.2 COAL AND CBM RESERVES

Coal is the most abundant and economical fossil fuel resource in the world today. Over the past 200 years, it has played a vital role in the stability and growth of the world economy. The current world human population of about 7000 million consumes $5 \times 10^{20}$ J of energy per year. It is expected to increase to $7.5 \times 10^{20}$ J/year in the next 20 years. About 87% of all energy consumed today is provided by fossil fuels. Nuclear and hydropower provide 12%. Solar, wind and geothermal energy provide barely 1% [2] as shown in Table 1.1.

Barring a breakthrough in nuclear fusion, fossil fuels will remain the main source of energy in the foreseeable future, as they have been for the past 200 years. Ninety percent of all fossil fuel energy in the world is in coal seams. It is, therefore, essential that coal’s share in the energy mix should increase. At present, coal provides 26% of global energy demand.
and generates 41% of the world’s electricity. Coal deposits are widespread in 70 countries of the world. Coal is a very affordable and reliable source of energy. The total proved, mineable reserve of coal exceeds 1 T ton to a depth of about 3300 ft (1000 m). Indicated reserves (mostly nonmineable) to a depth of 10,000 ft (3000 m) range from 17 to 30 T ton [3]. Current (2014) world coal production is about 8000 million ton/year. Coal production from the top ten countries is shown in Table 1.2.

Total tonnage mined in these 10 countries comprise nearly 90% of global production. Coal production may continue to increase if they start converting coal into synthetic gas and liquid fuels, such as, diesel and aviation fuels.

### Table 1.1 World energy reserves & consumption

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Energy consumed (EJ/y)</th>
<th>Proved reserves (ZJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>120</td>
<td>290</td>
</tr>
<tr>
<td>Gas</td>
<td>110</td>
<td>15.7</td>
</tr>
<tr>
<td>Oil</td>
<td>180</td>
<td>18.4</td>
</tr>
<tr>
<td>Nuclear</td>
<td>30</td>
<td>2−17(^c)</td>
</tr>
<tr>
<td>Hydro</td>
<td>30</td>
<td>N.A.</td>
</tr>
<tr>
<td>All others</td>
<td>4</td>
<td>Uncertain</td>
</tr>
</tbody>
</table>

\(^a\)E = 10^{18}.
\(^b\)Z = 10^{21}.
\(^c\)Reprocessing not considered. 1000 J = 0.948 BTU.

### Table 1.2 Global coal production

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual production (metric)(^a) t (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>3561</td>
</tr>
<tr>
<td>United States</td>
<td>904</td>
</tr>
<tr>
<td>India</td>
<td>613</td>
</tr>
<tr>
<td>Indonesia</td>
<td>489</td>
</tr>
<tr>
<td>Australia</td>
<td>459</td>
</tr>
<tr>
<td>Russia</td>
<td>347</td>
</tr>
<tr>
<td>South Africa</td>
<td>256</td>
</tr>
<tr>
<td>Germany</td>
<td>191</td>
</tr>
<tr>
<td>Poland</td>
<td>143</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>120</td>
</tr>
</tbody>
</table>

\(^a\)1 metric ton = 1.1 short tons.

Besides the minable coal reserve, the vast deep-seated deposits of coal contain another source of energy; CBM. It is almost like natural gas with a slightly lower (10–15%) calorific value. Reserve estimates of CBM in coal ranges from 275 to 33,853 TCF (78–959 Tm³) as shown in Table 1.3.

Fig. 1.1 shows the major coal basins around the world [8]. A brief description of only reservoir data for prominent basins is provided below. Other information is provided in the book *Coal Bed Methane from Prospect to Pipeline* [9].

### 1.2.1 US Coal Basins

Not counting Alaska, there are three major basins in the United States, as shown in Fig. 1.2.

1. The Western United States
2. The Illinois basin
3. The Appalachian basin

These regions can be further divided into 14 sub-basins with additional information [10], but only larger basins are discussed here.

<table>
<thead>
<tr>
<th>Table 1.3 Estimates of CMB reserve</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Country</strong></td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>United States</td>
</tr>
<tr>
<td>Russia</td>
</tr>
<tr>
<td>China</td>
</tr>
<tr>
<td>Canada</td>
</tr>
<tr>
<td>Australia</td>
</tr>
<tr>
<td>Germany</td>
</tr>
<tr>
<td>India</td>
</tr>
<tr>
<td>South Africa</td>
</tr>
<tr>
<td>Poland</td>
</tr>
<tr>
<td>Other countries</td>
</tr>
<tr>
<td>Total gas in place (GIP)</td>
</tr>
</tbody>
</table>

Recoverable Reserve: 30–60% of GIP.
US Conventional Gas Reserve 875 TCF (25 Tm³).
US EPA, 2009 [7].
Figure 1.1 Major coal basins of the world.

Figure 1.2 Major US coal basins.
1.2.1.1 The Western United States. It has the Following Sub-Basins

1. **San Juan basin** (Colorado, New Mexico). The basin covers an area of 14,000 mile$^2$. Coal seams with a thickness of 15–50 ft occur to a depth of 6500 ft with a total thickness of 110 ft. Gas content of coal varies from 300 to 600 ft$^3$/t. The coal is of low to high volatile bituminous rank. Permeability is medium to high (1–50 md). It is a well-developed field. Gas production is done by vertical, hydrofracked wells. Introduction of a new technology, horizontal boreholes (BH) drilled from the surface with hydrofracking, can increase gas production dramatically. A part of this basin is over-pressurized (gas pressure higher than hydrostatic pressure) leading to very high gas productions.

2. **Piceance basin** (W. Colorado). The basin covers an area of about 7000 mile$^2$. The thickness of coal seams varies from 20 to 30 ft with a total of up to 200 ft. The depth of coal seams varies from outcrop to 12,000 ft. The gas content of coal is 400–600 ft$^3$/t. The coal is of low grade. Permeability is generally low but there are areas where permeability of 1–5 md is indicated. Gas production is achieved by vertical drilling and hydrofracking. Gas production can be greatly increased by drilling horizontal BH from the surface and hydrofracking.

3. **Powder River basin** (Wyoming and Montana). This is a large basin covering 26,000 mile$^2$. The thickness of coal seams varies from 50 to 200 ft with a total coal thickness of 150–300 ft. The depth of coal seams varies from outcrop to 2500 ft. The gas content of coal is low at about 70 ft$^3$/t. The rank of coal is low: lignite to sub-bituminous. Permeability is usually high, ranging from 50 to 1500 md. Current gas production is from a shallow depth of 1000 ft or less. Gas production is achieved by vertical wells. Because of high permeability, no hydrofracking is generally needed.

1.2.1.2 The Illinois Basin (Illinois, Kentucky, and Indiana)

This is one of the largest basins, with an area of 53,000 mile$^2$. The thickness of coal seams varies from 5 to 15 ft with a total of 20–30 ft. The depth of cover varies from 0 to 3000 ft. The rank of coal ranges from HVC to HVB bituminous. The gas content is low, from 50 to 150 ft$^3$/t. The permeability is high in shallow areas approaching 50 md. Gas production is realized by vertical drilling and hydrofracking to a depth of generally less than 1000 ft. Hydrofracking of shallow coal is very inefficient. Horizontal BH drilled from the surface would be much more productive. No hydrofracking of horizontal BH is needed at shallow depths up to 1500 ft.
1.2.1.3 The Appalachian Basin (Pennsylvania, West Virginia, Virginia, Ohio, Maryland, Kentucky, Tennessee, and Alabama)

From a gas production point of view, the basin can be divided into two regions:

a. Northern Appalachia, and
b. Central and Southern Appalachia

1.2.1.3.1 Northern Appalachian Basin (Pennsylvania, West Virginia, Ohio, Kentucky, and Maryland)

This is a large basin with an area of about 45,000 mile$^2$ and it has been most extensively mined for the past 100 years. The thickness of coal seams vary from 4 to 12 ft with a total thickness of 25–30 ft. The depth of cover varies from 0 to 2000 ft. The coal rank varies from low volatile to high volatile bituminous coal. The gas content of coal seams ranges from 100 to 250 ft$^3$/t. The permeability to a depth of 1200 ft varies from 10 to 100 md. Gas production is mainly realized by drilling horizontal BH in the coal seam from the surface and in-mine workings. The specific gas production from various coal seams varies from 5 to 20 MCFD/100 ft of horizontal BH. This is the initial production from a freshly drilled BH. The total gas reserve is 61 TCF.

1.2.1.3.2 Central and Southern Appalachian Basin (West Virginia, Virginia, Kentucky, Tennessee, and Alabama)

The combined area of the basin is about 46,000 mile$^2$. The thickness of coal seams varies from 5 to 10 ft with a total thickness of 25–30 ft. The depth of cover varies from 1000 to 3000 ft. Mining depth generally does not exceed 2500 ft. The gas content of coal varies from 300 to 700 ft$^3$/t. The rank of coal is from low vol. to high vol. A bituminous. The permeability of coal seams varies from 1 to 30 md. Specific gas production from horizontal BH is 5–10 MCFD/100 ft. The main gas production technique is vertical drilling with hydrofracking. For commercial gas production, multiple coal seams are hydrofracked in a single well. Gas production of 250–500 MCFD is quite common for a single well completed in 3–5 coal seams. The total gas reserve is estimated at 25–30 TCF.

The CBM industry in the United States is well established. Nearly 50,000 wells have been completed with a total annual production of 1.8 TCF (about 10% of total US gas production). It can be easily doubled if the new technology of horizontal BH drilled from the surface and hydrofracking is applied to western thick coal seams.
1.2.2 Coal Basins of Canada

Most of the coal deposits in Canada are located in the provinces of Alberta and British Columbia, spread over a vast area of almost 400,000 mile$^2$, but only a small area is amenable to CBM production. This is the area where deep mining is done. Coal seams are generally thick (30—40 ft) and highly inclined. They occur near the boundary between Alberta and British Columbia. The four best prospects are in Horseshoe Canyon, Pembina, Mamille, and Alberta/BC foothills, with a total reserve of about 4—50 TCF. Vertical drilling with hydrofracking can be used for gas production to a depth of 3000 ft. For deeper formations, horizontal drilling from the surface with hydrofracking will be more productive.

The CBM industry in Canada has not reached its full potential, even though 3500 CBM wells have been drilled in Alberta and they are producing 100 BCF (2.5 Bm$^3$) annually. Projected forecast for CBM production is at 512 BCF/year (14.5 Bm$^3$) by 2015 [11]. Reservoir characteristics are largely unknown but a gas content of 300 ft$^3$/t at a depth of 1000 ft was measured near Hinton, BC, in the Jewel seam (internal, unpublished reports by the author). The permeability is about 10 md at this depth. The coal rank is bituminous to low-volatile coking coal.

1.2.3 Western Europe (The United Kingdom, France, and Germany)

These countries have a long history of coal mining. All shallow coal seams are almost mined out. The potential for gas production lies in deeper (3000 ft and deeper) coal seams. However, gas emitted by abandoned mines is being actively collected and utilized.

1.2.3.1 The United Kingdom

There are five major coal producing areas, i.e., Central Valley, northern area, eastern area, western area, and South Wales, with a potential for CBM production. The estimated recoverable gas reserve exceeds 100 TCF. Only a limited effort has been made to drill vertical wells and hydrofrack them but the results are rather disappointing. This technique is likely to succeed only in South Wales, where the geological characteristics of coal seams are favorable. For the rest of the deeper coal deposits, the only technique that has a potential to produce gas at commercial production rates is horizontal BH drilled from the surface with sequential
hydrofracking. The coal seams are generally thin and the permeability is very low. Reservoir properties are shown in Table 1.4 [12].

1.2.3.2 France
The best gas production potential is in the eastern France, the Lorraine—Sarre basin. Coal deposits are deeper than 3000 ft with a total CBM reserve of 15 TCF. Most of the coal is of high volatile bituminous rank and is gassy. The basin covers nearly 3000 mile$^2$. Reservoir properties are shown in Table 1.4 [13].

Based on personal experience, vertical drilling and hydrofracking is not likely to succeed for seams deeper than 3000 ft. Horizontal BH drilled from the surface combined with hydrofracking is likely to succeed.

1.2.3.3 Germany
The estimated recoverable reserve of deep coal is about 183 million tons but about 7 billion tons (mostly lignites) are indicated with a CBM reserve of over 100 TCF. Mining to a depth of 3000—4000 ft was done in the Ruhr and Saar coal basins. The Saar basin has an area of only 440 mile$^2$. Coal seams are of medium thickness with very low permeability. Vertical drilling with hydrofracking was tried but with limited success [14]. Reservoir properties are shown in Table 1.4 [14]. Again, the best method to produce commercial quantities of CBM from these coal
seams is to drill horizontal BH from the surface and hydrofrack the horizontal legs. Germany has a large reserve of lignite but it is not a reserve for CBM.

1.2.4 Eastern Europe (Poland, Czech Republic, Ukraine)

1.2.4.1 Poland
The total reserve of hard (and deep) coal is estimated at 100 billion tons with a CBM reserve of 20–60 TCF. The major potential for CBM production is in the upper and lower Silesian basins, which border and extend into Czechoslovakia. Mining has been done to a depth of 3500 ft. Hence all potential reserves of CBM are deeper than that. The gas content of coal seams is high at 635–950 ft³/t (18–27 m³/t). Vertical drilling with hydrofracking were planned but results, if any, are not known. The gas production technique that is likely to succeed is horizontal BH drilled from the surface with hydrofracking at 1000 ft intervals.

1.2.4.2 Czech Republic
CBM production potential exists mainly in the upper Silesian basin, also known as the Ostrava-Karvina basin. The basin has an area of 600 mile² and has many coal seams with a total thickness of about 500 ft. Coal seam gas content is similar to Polish coal fields and is in excess of 700 ft³/t (20 m³/t). This provides an excellent opportunity for commercial CBM production using both vertical wells completed in multiple horizons to a depth of 3300 ft (1000 m) and horizontal BH drilled from the surface with hydrofracking at 1000 ft intervals in deeper coal seams. Preliminary efforts at vertical drilling and hydrofracking by a British firm did not succeed [15] but the process needs to be investigated for improvement.

1.2.4.3 Ukraine
In Ukraine, there are 330 coal seams to a depth of 6000 ft (1800 m) but only 10 are amenable to CBM development [16]. The remaining seams are too thin for commercial exploration. The Donetsk basin (also called Donbass) is the main area of interest. The recoverable coal reserve is estimated at 213 billion tons with a CBM reserve of 63 TCF (1.8 Tm³). Very little is known about whether any effort to produce CBM commercially has been made. The coal seams are of low vol to high vol bituminous rank and likely to contain 300–600 ft³/t of CBM. Seam properties are similar to those in the central Appalachian basin of the United States.
1.2.5 Russia

As shown in Table 1.3, Russia has the largest coal reserves and hence the largest CBM reserves in the world. The lower estimate ranges from 2600 to 2800 TCF (75–80 Tm$^3$). With the abundance of natural gas and oil deposits, Russia has no incentive to produce CBM from its coal deposits. Only about 30% of Russia’s coal reserve is of high rank, which is the reservoir for CBM. Areas of interest are in the Donbass (next to Ukraine), Pechora, Karganda, and Kuznetsk basins. The vast majority of Russian coal is of low rank, which does not contain much CBM. Hard coals occur to a depth of 8000 ft (2500 m). Only rudimentary efforts have been made to drill vertical wells with hydrofracking. Four experimental wells drilled to a depth of 2000–3000 ft produced only 35–100 MCFD. This is low compared to US CBM wells. A better technique to produce CBM would be to use horizontal BH drilled from the surface with hydrofracking of the horizontal legs at 1000 ft intervals.

1.2.6 China

China has a vast reserve of CBM, estimated at 1100 TCF (317 Bm$^3$) to a depth of 6500 ft (2600 m). There are four areas of coal deposit that contain most of the recoverable CBM: (a) Northern (56.3%), (b) Northwestern (28.1%), (c) Southern (14.3%), and (d) North Eastern (1.3%) (US EPA, 2009). The Chinese CBM industry is off to a good start with some help from the US EPA. More than a thousand vertical CBM wells have been drilled and production enhanced by hydrofracking. Current CBM production is estimated at 130 BCF (4 Mm$^3$) per year and is increasing. CBM production from shallow minable coal (to a depth of 3000 ft) has become necessary for mine safety. Mine explosions and resulting fatalities are still quite high in China. While vertical drilling with hydrofracking should produce high rates of gas production in all coal fields of China, they must consider using horizontal BH drilled from the surface with hydrofracking for coal seams deeper than 3300 ft (1000 m).

1.2.7 India

Although India has 17 coal fields with a total coal reserve of 200 billion tons, only three basins are viable reserves for CBM, namely Ranigunj (West Bengal), Jharia (Jharkhand), and Singrauli (Madhya Pradesh). The deep coal is of high rank with a gas content of 100–800 ft$^3$/t. Mines to a
depth of 4000 ft (1200 m) producing more than 10 m³/t (353 ft³/t) of methane for each ton of raw coal are considered Degree III gassy. The reserves of these mines are good candidates for CBM production. Recent estimates of CBM reserves by Indian agencies put the CBM reserve at 70–100 TCF (2–3.4 Tm³) [17]. Four blocks of coal covering an area of about 6000 mile² have been leased for CBM production. Over 100 wells have been completed but production data is not yet available. These are vertical wells completed in a single coal seam with hydrofracking. Coal seams are generally thin at greater depth. Some very thick seams (in Bihar and Odhisa provinces) at shallow depths may turn out to be good producers (like the Powder River basin of the United States) but attempts to produce CBM have not yet been made.

1.2.8 South Africa

The central part of the country containing the Witbank and Highfield basins is the best prospect for CBM production. Most of South Africa’s coal is produced from these two basins. The coal is of high rank but most coal seams are shallow. The average gas content is estimated at 300 ft³/t at a depth of 1000 ft. Preliminary efforts to drain methane by in-mine horizontal BH and vertical wells with hydrofracking are afoot but results are not available yet [18]. The estimated CBM reserve is low, at 5–10 TCF. Geological conditions of these basins (too shallow) preclude the use of vertical drilling and hydrofracking. Commercial gas production can only be obtained if horizontal BH are drilled from the surface and have a lateral extension of 3000–5000 ft. CBM production techniques used in the Northern Appalachian basin of the United States have a potential application in South Africa. Some methane gas has been captured from gold mines and used for many years but the subject is beyond the scope of this book.

1.2.9 Australia

The best prospect of CBM production lies in the Bowen basin (Queensland) and the Sydney basin (New South Wales). The latest estimate of CBM in these basins is about 7 TCF. The Sydney basin coal seams are deeper and gassier with a gas content of 350–700 ft³/t (10–20 m³/t) and, as such, more amenable to gas production by vertical wells with hydrofracking. In-mine horizontal drilling has shown fairly good specific gas production of 8–10 MCFD/100 ft of BH. Well-designed wells with multiple completion in several coal seams can
produce 200–300 MCFD per well. Bowen basin coal seams have been extensively drilled, with over 500 wells. Annual gas production from this basin is estimated at 100 BCF which is about 90% of total Australian CBM production. Vertical drilling and hydrofracking is unlikely to be very productive in the Bowen basin because of its shallow depth. Horizontal drilling from the surface is the best technique to produce gas from these shallow coal seams. Hydrofracking may not be needed but actual gas production from such BH will dictate it. However, even the current low CBM production is providing up to 48% of Queensland’s gas supply [7].

### 1.2.10 Other Coal-Producing Countries

Even though there is a general lack of reliable data, there are potentially good CBM reserves in many countries other than those listed above. The ideal way to locate and prove a CBM reserve is to drill the area on a grid pattern, collect cores, and measure the gas content. Where such data are not available, one can use some general guidelines to locate a potential CBM reserve.

1. All deep, thick seams of high rank coal are potential CBM reserves.
2. Very thick coal seams (100–300 ft) can be good reserves even if they are shallow and of low rank. The Powder River basin is a good example.
3. The reserves of coal mines that have high specific methane emissions are also a potential reserve. The specific methane emission of a mine is the volume of methane produced per ton of raw coal mined. It is linearly related to the depth of the coal seam as shown in Fig. 1.3 [19]. Coal reserves where mines have a specific methane emissions of more than 700 ft³/t (20 m³/t) are potentially good reserves.

In conclusion, it must be noted that even though there is vast potential for CBM production worldwide, production growth is controlled by a number of nontechnical factors. The main three are:

1. The current over-supply of natural gas in the world.
2. Lack of equipment and technology outside the United States for horizontal completions from the surface.
3. Environmental laws, particularly in Europe, driving the cost very high. A typical water injection well drilled in Eastern Europe will cost three times more than a similar well in the Central Appalachian basin of the United States.

The drilling and completion techniques as well as the reservoir and production engineering for CBM are significantly different from those for
conventional natural gas wells drilled in sandstone and limestone. Table 1.5 shows some critical differences that justify the need for this book.

Gas production from coal, therefore, is a far more complicated process than that for natural gas from sandstone/limestone reservoirs. The purpose of this book is to present reservoir and production engineering for CBM in a simple, understandable language. The knowledge contained in
the book will help optimize gas production from all the above-listed prominent CBM reserves.

REFERENCES