6 COAL

Abstract

Coal is the primary source of energy for most of the countries in the world. Although the main use of coal is in the generation of electricity, recently synthesis of liquid fuel from coal is becoming attractive, although coal liquefaction is a very old and well known process that was developed just after World War I. This may relieve pressure on petroleum as the only source of automobile fuel. However, a major concern in the use of coal is emissions of various pollutants including gases that cause acid rain and CO_2 emissions – a major contributor to global warming. Two approaches are pursued to reduce emissions from coal power plants. Most of the recent coal power plants are designed to produce supercritical steam, increasing the efficiency to about 50%. Another approach is to develop zero emission coal power plants. In this chapter, a comprehensive discussion on the use of coal and associated issues are presented.

6.1 Introduction

Coal has a long and rich history. The commercial use of coal can be traced back to 1000 BC by China. However, there is evidence that coal has been used for heating by the cave men. Archeologists have also found evidence that the Romans in England used coal in the second and third centuries (100–200 AD). The first scientific reference to coal may have been made by the Greek philosopher and scientist Aristotle, who referred to a charcoal like rock. It was during the Industrial Revolution in the 18th and 19th centuries that demand for coal surged. The introduction of the steam engine by James Watt in 1769 was largely responsible for the growth in coal use.

Coal was discovered in the United States by explorers in 1673. However, the Hopi Indians used coal for cooking, heating and to bake the pottery during the 1300s. Commercial coal mines started operation around 1740s in Virginia. During

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the Civil War, weapons factories were beginning to use coal. By 1875, coke (which is made from coal) replaced charcoal as the primary fuel for iron blast furnaces to make steel.

The use of coal for electricity generation started around the nineteenth century. The first practical coal-fired electricity generating station, developed by Thomas Edison, went into operation in New York City in 1882, supplying electricity for household lights.

Coal was the primary source of energy until 1960s. The use of oil for transportation overtook coal as the largest source of primary energy in the 1960s. However, coal still plays a vital role in the world's primary energy mix, providing 24.4% of global primary energy needs in 2003 and 40.1% of the world's electricity. The production and consumption of coal by various regions and some selected countries are given in Tables 6.1 and 6.2. As can be seen from Table 6.2, the use of coal world wide is increasing slowly. In Table 6.3 shows how long the coal will last at the current rate of use and with modest increase in the next few years.

Table 6.1. Yearly coal production of selected countries in million tonnes.[a]

Countries	**Years**				**Share of the World (%)**
	2003	**2004**	**2005**	**2006**	
USA	972.3	1008.9	1026.5	1053.6	19.3
Canada	62.1	66.0	65.3	62.9	1.1
Mexico	9.7	9.9	10.0	11.1	0.2
Total North America	**1044.1**	**1084.8**	**1101.8**	**1127.7**	**20.5**
Brazil	4.7	5.4	6.3	6.3	0.1
Colombia	50.0	53.7	60.6	65.6	1.4
Venezuela	7.0	8.1	8.1	8.1	0.2
Other S. & Cent. America	0.5	0.3	0.8	0.7	–
Total S. & Cent. America	**62.2**	**67.5**	**75.7**	**80.7**	**1.7**
Bulgaria	27.3	26.6	26.4	27.5	0.2
Czech Republic	63.9	62.0	62.0	62.4	0.8
France	2.2	0.9	0.6	0.5	–
Germany	204.9	207.8	202.8	197.2	1.6
Greece	71.0	71.6	70.6	70.6	0.3
Hungary	13.3	11.5	9.6	10.0	0.1
Kazakhstan	84.9	86.9	86.6	96.3	1.6

Countries	Years				Share of the World (%)
	2003	2004	2005	2006	
Poland	163.8	162.4	159.5	156.1	2.2
Romania	33.1	31.8	31.1	35.1	0.2
Russian Federation	276.7	281.7	298.5	309.2	4.7
Spain	20.5	20.5	19.4	18.4	0.2
Turkey	49.3	49.9	61.7	63.4	0.4
Ukraine	80.2	81.3	78.7	80.5	1.4
United Kingdom	28.3	25.1	20.5	18.6	0.4
Other Europe & Eurasia	66.2	65.2	63.9	66.7	0.5
Total Europe & Eurasia	**1185.7**	**1185.1**	**1192.0**	**1212.4**	**14.5**
Total Middle East	**1.0**	**1.1**	**1.1**	**1.1**	**–**
South Africa	237.9	243.4	244.4	256.9	4.7
Zimbabwe	2.8	3.8	2.9	2.9	0.1
Other Africa	2.0	2.0	1.8	1.8	–
Total Africa	**242.7**	**249.2**	**249.0**	**261.6**	**4.8**
Australia	351.5	366.1	378.8	373.8	6.6
China	1722.0	1992.3	2204.7	2380.0	39.4
India	375.4	407.7	428.4	447.3	6.8
Indonesia	114.3	132.4	146.9	195.0	3.9
Japan	1.3	1.3	1.1	1.3	–
New Zealand	5.2	5.2	5.3	5.8	0.1
Pakistan	3.3	3.3	3.5	4.3	0.1
South Korea	3.3	3.2	2.8	2.8	–
Thailand	18.8	20.1	20.9	19.4	0.2
Vietnam	19.3	26.3	32.6	38.9	0.7
Other Asia Pacific	37.5	40.0	41.9	43.1	0.7
Total Asia Pacific	**2651.8**	**2997.7**	**3267.0**	**3511.7**	**58.5**
TOTAL WORLD	**5187.6**	**5585.3**	**5886.7**	**6195.1**	**100.0**

[a]Commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal.

Annual changes and shares of total are based on data expressed in tonnes oil equivalent. Because of rounding some totals may not agree exactly with the sum of their component parts.

Source: Reference [1].

Table 6.2. World coal consumption by regions and of selected countries.

Region/Country	2002	2003	2004	% of World in 2004
World Total	5,262.80	5,698.15	6,098.78	
Asia & Oceania	2,448.45	2,795.88	3,190.25	52.31
North America	1,151.89	1,182.43	1,182.53	19.39
Europe	1,030.01	1,052.40	1,036.30	16.99
Eurasia	398.01	413.30	429.40	7.04
Africa	184.44	200.33	205.83	3.37
Central & South America	35.92	37.57	38.21	0.63
Middle East	16.07	16.23	16.27	0.27
China	1,412.96	1,720.24	2,062.39	33.82
United States	1,065.84	1,094.86	1,107.25	18.16
India	434.44	448.62	478.16	7.84
Germany	278.98	277.29	279.95	4.59
Russia	240.23	243.43	257.52	4.22
Japan	173.47	185.24	203.72	3.34
South Africa	169.56	186.60	195.14	3.20
Australia	145.37	142.64	150.09	2.46
Poland	149.45	155.49	153.10	2.51
Ukraine	71.51	75.39	77.50	1.27
Korea, South	81.47	83.13	90.56	1.48
Greece	76.81	78.16	80.34	1.32
Turkey	73.16	70.65	69.59	1.14
Canada	72.21	68.88	57.76	0.95
Kazakhstan	66.24	72.32	72.86	1.19
Czech Republic	64.65	65.58	63.43	1.04
United Kingdom	64.17	68.78	67.16	1.10
Taiwan	56.32	60.67	62.90	1.03
Spain	50.53	46.68	48.67	0.80
Korea, North	31.99	32.58	33.07	0.54
Other Countries				8.00

Source: Reference [1].

Table 6.3. Years coal will last at various consumption rate.

Country	Current consumption (2004)	Total reserve	Consumption time in year with the following growth rate annually							
			0%	2%	2.50%	3.00%	3.50%	4%	4.50%	5%
China	2,062.39	126,215	61.20	40.36	37.59	35.26	33.28	31.56	30.05	28.72
United States	1,107.25	271,677	245.36	89.69	79.57	71.84	65.71	60.70	56.53	52.99
India	478.16	93,031	194.56	80.16	71.63	65.03	59.75	55.40	51.75	48.63
Germany	279.95	72,753	259.88	92.12	81.58	73.56	67.21	62.04	57.73	54.08
Russia	257.52	173,074	672.08	134.84	116.61	103.26	93.01	84.85	78.19	72.64
Japan	203.72	852	4.18	4.06	4.03	4.00	3.97	3.94	3.92	3.89
South Africa	195.14	54,586	279.73	95.25	84.18	75.78	69.14	63.76	59.28	55.49
Australia	150.09	90,489	602.90	129.75	112.47	99.77	89.99	82.19	75.81	70.48
Poland	153.1	24,427	159.55	72.36	65.09	59.39	54.78	50.97	47.75	44.98
Ukraine	77.5	37,647	485.77	119.77	104.32	92.88	84.02	76.92	71.09	66.21
Greece	80.34	3,168	39.43	29.36	27.78	26.41	25.21	24.14	23.18	22.32
Turkey	69.59	4,066	58.43	39.09	36.47	34.26	32.37	30.73	29.28	28.01
Canada	57.76	7,251	125.54	63.42	57.52	52.83	48.99	45.78	43.04	40.68
Kazakhstan	72.86	37,479	514.40	122.39	106.47	94.70	85.60	78.32	72.34	67.34
Czech Republic	63.43	6,259	98.68	55.03	50.35	46.56	43.42	40.76	38.48	36.50
UK	67.16	1,653	24.61	20.21	19.42	18.71	18.06	17.47	16.94	16.44
Spain	48.67	728	14.96	13.22	12.87	12.54	12.24	11.96	11.69	11.45
Korea, North	33.07	661	19.99	16.98	16.41	15.89	15.42	14.98	14.58	14.20

6.2 Origin of Coal

Two main theories have been suggested by scientists on the origin of coal or how coal is formed [2–4]. According to the first theory, coal formed in situ, where the vegetation grew and fell, and such a deposit is said to be autochthonous in origin. The starting constituents of coal are believed to be plant debris, trees, and bark that accumulated and settled in swamps. Composition of coals differs throughout the world due to the kinds of plant materials involved in the formation (type of coal), in the degree of metamorphism or coalification (rank of coal), and in the type of impurities included (grade of coal). However, there is a great controversy on the bearing of plant constituents, particularly cellulose and lignin, on coal formation.

The unconsolidated accumulation of plant remains is called peat. The beginning of most coal deposits started with thick peat bogs where the water was nearly stagnant and plant debris accumulated. The plant debris converted into peat by microbiological action. Over the years, these layers of peat became covered with sediment and were subjected to heat and pressure from the subsidence of the swamps. The cycles of accumulation and sediment deposition continued and were followed by diagenetic (i.e., biological) and tectonic (i.e., geological) actions and, depending upon the extent of temperature, time, and forces exerted, formed the different ranks of coal observed today [5–19]. A number of researchers concluded that cellulose in plants was the main path towards the ultimate formation of coal [20–28]. Both the theories were reviewed by several groups and their applicability to various deposits around the world was discussed. However, it became certain from these reviews that one single theory could not be applied to explain all the deposits [29–48].

A metamorphic process, called coalification as shown in Fig. 6.1, eventually formed the coal. The metamorphic process is thought to have occurred in several stages and the factors assumed to affect the content, makeup, quality, and rank of the coal are given below.

- Temperature
- Pressure
- Time
- Layering process
- Fresh water/sea water
- Swamp acidity
- Types of plant debris
- Types of sediment cover

Plant materials are first converted to peat that has high moisture content and a relatively low heating value. However, as the process of coalification continues under greater pressure and temperature, peat starts to loose moisture and other types of coal formed.

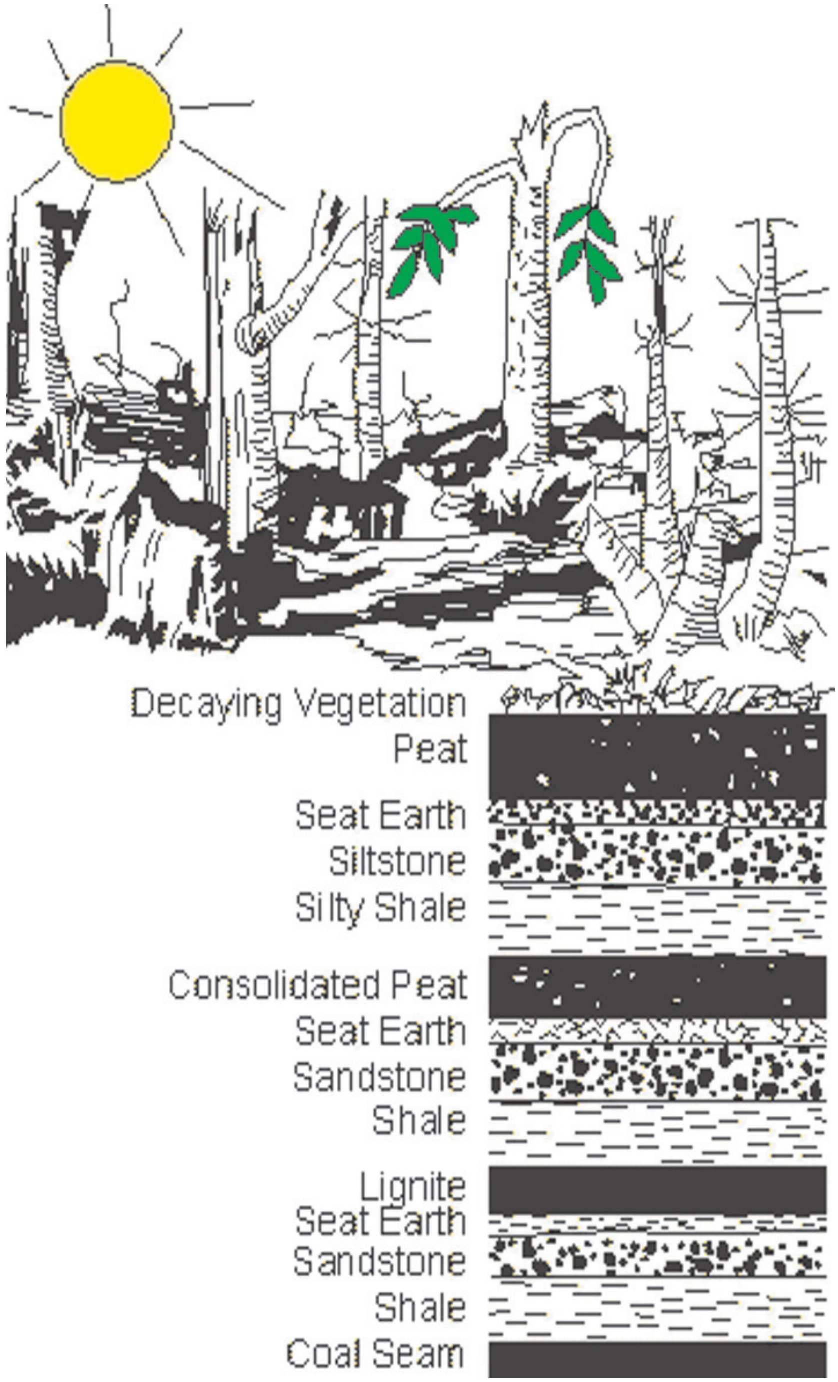


Fig. 6.1. Coal formation process. (Adapted from [49]).

The mineral content in coal comes from the salts that were part of the body of water. This generally leads to different mineral contents in various coal deposits. Ash content is due to the mud (may be considered as a mixture of mineral) that was deposited along with the plant matter. Different bodies of water had different rates of mud deposit.

In the USA, eastern coal is the oldest and formed from the organic debris in a shallow sea. Eastern coal is high in sulfur because the seas it formed in were high in sulfur salts. Nearly all eastern coal is bituminous. There is a small amount of anthracite in the east. Western coal is relatively young. It formed mostly in fresh water swamps. It contains less sulfur because there was relatively little sulfur salts in the water. It has more ash because the rate of mud deposit in a swamp is high. Western coal is mostly sub-bituminous or lignite.

The second theory stipulates that coal formed through the accumulation of vegetal matter that has been transported by water to another location [3, 4]. According to this theory (i.e., allochthonous origin), the fragments of plants were carried away by streams and deposited on the bottom of the sea or in lakes where they build up strata, which later became compressed into coal. Major coal deposits were formed in every geological period since the Upper Carboniferous Period, 350–270 million years ago. The main coal-forming periods are shown in Fig. 6.2, which shows the relative ages of the world’s major coal deposits.

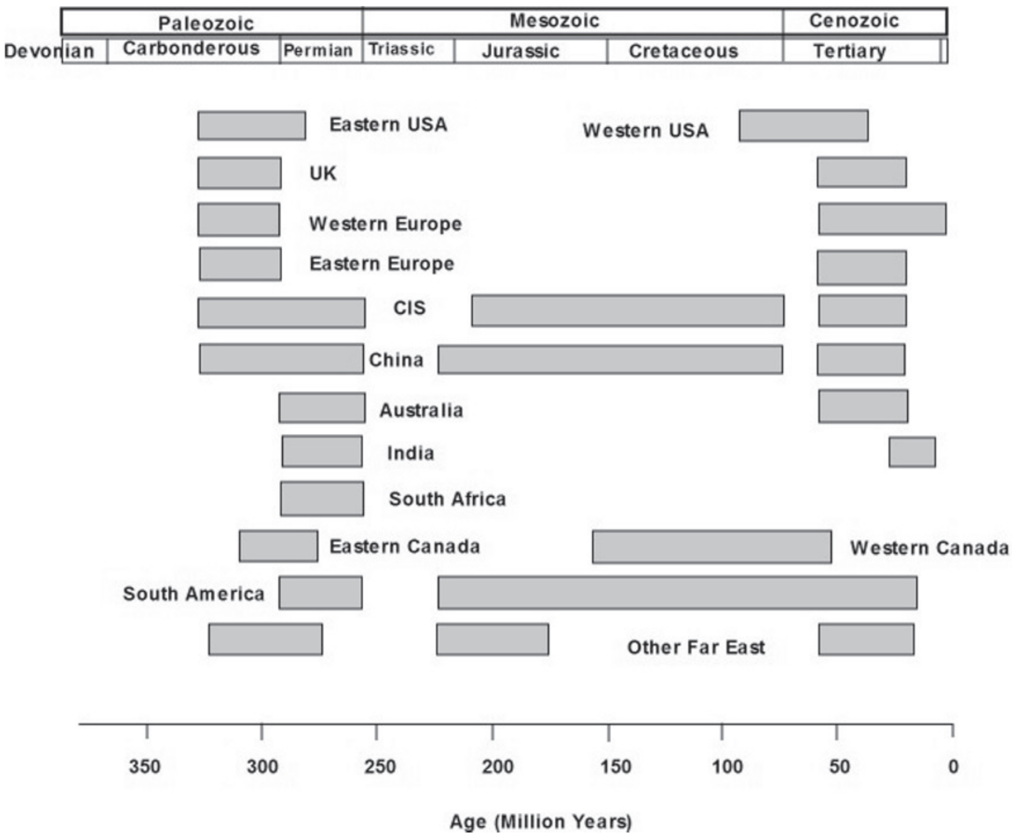


Fig. 6.2. Ages of coal at different parts of the world. (Printed with permission from [50]).

6.3 Classification

Coal is generally divided into two main categories: Anthracite (or Hard Coal) and Bituminous (or Soft Coal). The classification is mainly based on the carbon content and moisture content of the coal. As the coalification process continues the rank of the coal increases. The rank of coal is defined as the degree of changes (metamorphism) that occurs as a coal matures from peat to anthracite. The coal may be classified in a number of ways as described below. There are a number of subdivisions within these categories too.

1. By ash content
   Low ash (<5%)
   High ash (>20%)
2. Its structure
   Anthracite (nearly pure carbon)
   Bituminous (more bound hydrogen)
   Sub-Bituminous (less bound hydrogen)
   Lignite
3. Heating values
   Anthracite: 22–28 x 10^6 BTU/ton
   Bituminous: 25 x 10^6 BTU/ton
   Lignites: 12 x 10^6 BTU/ton
4. Sulfur content
   Low (<1%)
   High (about 7%)
5. Coke grade
   Metallurgical coke (premier grade)
   Non metallurgical coke (low grade)
6. Caking properties
   Caking
   Non-caking

The American Society of Testing and Material (ASTM) has a standard classification of coals by ranks and is provided in their D388-84, which is given in Table 6.4.

The four main constituents of coal are volatile matters, hydrogen, carbon, and oxygen. The percentage of these elements determines the heating value of coal rank. The C/H and (C+H)/O ratios are also important for determining combustion characteristics of coal. These values for different ranks of coal are shown in Table 6.5.

Table 6.4. Classification of coal by rank according to ASTM standard 388.

Class	Group	Fixed carbon limits (%) (dry mineral matter free basis)		Volatile matter limits (%) (dry, mineral matter free basis)		Calorific value limits (BTU/lb) (moist mineral matter free basis)		Agglomerating character
		Equal to or greater than	Less than	Greater than	Equal to or less than	Equal to or greater than	Less than	
I. Anthracite	1. Meta-anthracite	98	–	–	2	–	–	Non-agglomerating
	2. Anthracite	92	98	2	8	–	–	
	3. Semi-anthracite	86	92	8	14	–	–	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	–	–	Commonly agglomerating
	2. Medium volatile bituminous coal	69	78	22	31	–	–	
		–	69	31	–	14,000	–	
	3. High volatile A bituminous coal	–	–	–	–	13,000	14,000	
		–	–	–	–	11,500	13,000	
	4. High volatile B bituminous coal	–	–	–	–	10,500	11,500	Agglomerating
	5. High volatile C bituminous coal							
III. Subbituminous	1. Subbituminous A coal	–	–	–	–	10,500	11,500	Non-agglomerating
	2. Subbituminous B coal	–	–	–	–	9,500	10,500	
	3. Subbituminous C coal	–	–	–	–	8,300	9,500	
IV. Lignite	1. Lignite A	–	–	–	–	6,300	8,300	Non-agglomerating
	2. Lignite B	–	–	–	–	–	6,300	

(a) This classification applies to coals composed mainly of volatile: coals rich in liptinite or inertinite do not fit into this classification system.
(b) Standard units for ASTM classification for calorific value are BTU/lb. To convert to SI units of kJ/kg, multiply BTU/lb by 2.326.
(c) Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.
(d) If agglomerating, classify in low-volatile group of the bituminous class.
(e) Coals having 69% or more fixed carbon on a dry, mineral matter free basis are classified according to fixed carbon only, regardless of calorific value.
(f) It is recognized that there may be non-agglomerating varieties in these groups of bituminous class, and that there are notable exceptions in the high volatile C bituminous group.
(g) Agglomerating coals in the range 10,500–11,500 BTU/lb are classed as high volatile C bituminous coal.

Source: ASTM Standard D388-84 (1984).

Table 6.5. Classification profile chart.

	Average analysis-moisture and ash free basis						
	Volatile matter (%)	Hydrogen (wt%)	Carbon (wt%)	Oxygen (wt%)	Heating value (kJ/kg)	C/H ratio	(C+H)/O ratio
Anthracite							
Meta	1.8	2.0	94.4	2.0	34,425	46.0	50.8
Anthracite	5.2	2.9	91.0	2.3	35,000	33.6	42.4
Semi	9.9	3.9	91.0	2.8	35,725	23.4	31.3
Bituminous							
Low-vol.	19.1	4.7	89.9	2.6	36,260	19.2	37.5
Med-vol.	26.9	5.2	88.4	4.2	35,925	16.9	25.1
High-vol. A	38.8	5.5	83.0	7.3	34,655	15.0	13.8
High-vol. B	43.6	5.6	80.7	10.8	33,330	14.4	8.1
High-vol. C	44.8	4.4	77.7	13.5	31,910	14.2	6.2
Sub-bituminous							
Sub-bitu. A	44.7	5.3	76.0	16.4	30,680	14.3	5.0
Sub-bitu. B	42.7	5.2	76.1	16.6	30,400	14.7	5.0
Sub-bitu. C	44.2	5.1	73.9	19.2	29,050	14.6	4.2
Lignite							
Lignite A	46.7	4.9	71.2	21.9	28,305	14.5	3.6

To convert kJ/kg to BTU/lb, divide by 2.326

Source: Reference [51]

The use of coal depends on its rank and their use is summarized in Table 6.6.

Table 6.6. Use of coal depending on its rank.

Types of coal	% of World reserves	Uses
Low rank coals		
Lignite	17	Mainly power generation
Sub-bituminous	30	Power generation
		Cement manufacture
		Industrial uses
Hard coal		
Bituminous	52	
Thermal steam coal		Power generation
		Cement manufacture
		Industrial uses
Metallurgical coking coal		Manufacture of iron and steel
Anthracite	1	Domestic/Industrial uses
		Smokeless fuel

Source: Reference [52].

The reserve of different ranks of coal in various countries is given in Table 6.7.

Table 6.7. Coal: proved reserves at the end 2006 (in million tones).

Country	Anthracite and bituminous	Sub-bituminous and lignite	Total	Share of world total	R/P ratio
USA	111,338	135,305	246,643	27.1%	234
Canada	3,471	3,107	6,578	0.7%	105
Mexico	860	351	1,211	0.1%	109
Total North America	**115,669**	**138,763**	**254,432**	**28.0%**	**226**
Brazil	–	10,113	10,113	1.1%	*
Colombia	6,230	381	6,611	0.7%	101
Venezuela	479	–	479	0.1%	60
Other S. & Cent. America	992	1,698	2,690	0.3%	*
Total S. & Cent. America	**7,701**	**12,192**	**19,893**	**2.2%**	**246**
Bulgaria	4	2,183	2,187	0.2%	80
Czech Republic	2,094	3,458	5,552	0.6%	89

(Continued)

Table 6.7. (Continued)

Country	Anthracite and bituminous	Sub-bituminous and lignite	Total	Share of world total	R/P ratio
France	15	–	15	◆	30
Germany	183	6,556	6,739	0.7%	34
Greece	–	3,900	3,900	0.4%	55
Hungary	198	3,159	3,357	0.4%	337
Kazakhstan	28,151	3,128	31,279	3.4%	325
Poland	14,000	–	14,000	1.5%	90
Romania	22	472	494	0.1%	14
Russian Federation	49,088	107,922	157,010	17.3%	*
Spain	200	330	530	0.1%	29
Turkey	278	3,908	4,186	0.5%	66
Ukraine	16,274	17,879	34,153	3.8%	424
United Kingdom	220	–	220	◆	12
Other Europe & Eurasia	1,529	21,944	23,473	2.6%	352
Total Europe & Eurasia	**112,256**	**174,839**	**287,095**	**31.6%**	**237**
South Africa	48,750	–	48,750	5.4%	190
Zimbabwe	502	–	502	0.1%	176
Other Africa	910	174	1,084	0.1%	*
Middle East	419	–	419	◆	399
Total Africa & Middle East	**50,581**	**174**	**50,755**	**5.6%**	**194**
Australia	38,600	39,900	78,500	8.6%	210
China	62,200	52,300	114,500	12.6%	48
India	90,085	2,360	92,445	10.2%	207
Indonesia	740	4,228	4,968	0.5%	25
Japan	359	–	359	◆	268
New Zealand	33	538	571	0.1%	99
North Korea	300	300	600	0.1%	20
Pakistan	–	3,050	3,050	0.3%	*
South Korea	–	80	80	◆	28
Thailand	–	1,354	1,354	0.1%	70
Vietnam	150	–	150	◆	4
Other Asia Pacific	97	215	312	◆	7
Total Asia Pacific	**192,564**	**104,325**	**296,889**	**32.7%**	**85**
TOTAL WORLD	**478,771**		**100.0%**	**147**	

Country	Anthracite and bituminous	Sub-bituminous and lignite	Total	Share of world total	R/P ratio
European Union 25	17,424	17,938	35,362	3.9%	65
European Union 27	17,450	20,593	38,043	4.2%	63
OECD	172,363	20,0857	373,220	41.1%	177
Former Soviet Union	94,513	132,741	227,254	25.0%	464
Other EMEs	211,895	96,695	308,590	33.9%	86

*More than 500 years.

◆Less than 0.05%.

Proved reserves of coal – Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known deposits under existing economic and operating conditions.

Reserves/Production (R/P) ratio – If the reserves remaining at the end of the year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate.

Source: References [1, 53].

The exports and imports of coal by various countries are given in Appendix VI.

6.4 Coal Properties and Structure

The analysis of coal is carried out not only to determine its rank, but also its combustion characteristics. The results of these analyses can be used to predict coal behavior and the corresponding environmental impact during its use. Analysis of coal must be carried out using established protocols and standard methods described by American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO) and British Standards Institution (BSI) test method numbers. These standards are listed in Table 6.8. Descriptions and objectives of these analyses are described in Table 6.9.

Table 6.8. ASTM and corresponding ISO methods for coal analysis.

Parameter	ASTM method	ISO method	BSI
Ultimate analysis		ISO 17247:2005	BS 1016-6
Proximate	D-5142	ISO 17246	BS 1016 P104
Sulfur	D-4239	ISO 334 and ISO 351	BS 1016 P106 S106.4.2
Carbon & hydrogen	D-5373	ISO 609 and 625	BS 1016 P106 SS106.1.1

(Continued)

Table 6.8. (Continued)

Parameter	ASTM method	ISO method	BSI
Nitrogen	D-5373	ISO 333	BS 1016 P106 S106.2
BTU	D-2015		
Forms of sulfur	D-2492	ISO 157	BS 1016 P106 S106.5
HGI	D-409		
Trace elements by ICP	D-6357		
Trace elements by rf-source GDMS	N/A		
Moisture	D-1412	ISO 589	BS 1016 P104 S104.1
Specific gravity	D-167		
Sulfur in ash	D-5016		
Ash fusion temp.	D-1857	ISO 540	BS 1016 P113
Mineral ash	D-4326	ISO 1171	
Sieve analysis	D-4749		BS 1016 P109
Sample prep.	D-2013		BS1017 P1
Washability	D-4371		
Chloride	D-4208		
Mercury	D-3684	ISO 15237	
Arsenic		ISO 601	BS 1016 P10
Phosphorous		ISO 622	BS 1016-9
Petrographic analysis		ISO 7404	BS 6127
Mineral matter		ISO 602	
Abrasiveness		ISO 12900	BS1016 P111

Table 6.9. Description and objectives of various coal analysis techniques.

Properties	Description of the analysis
Chemical properties	
Proximate analysis	Determination of the “approximate” overall composition of a coal, i.e., moisture, volatile matter, ash, and fixed carbon content.
Ultimate analysis	Absolute measurement of the elemental composition of coal excluding ash elements.
Atomic ratio	The H/C and O/C chemical analysis of coal.
Elemental analysis	Measurement of elements in coal including ash elements.
Sulfur forms	Chemically bonded sulfur in coal: organic, sulfide, or sulfate.
Physical properties	
Density	True density measured by helium displacement, minimum of 1.3 g/mL at 85–90% C.

Properties	Description of the analysis
Specific gravity	Apparent density – use of fluid that does not penetrate pores.
Pore structure	Specification of the porosity of coals and nature of pore structure between macro, micro, and transitional pores.
Surface area	Determination of surface area by nitrogen or carbon dioxide adsorption.
Reflectivity	Useful in petrographic analyses.
Mechanical properties	
Elasticity	Quality of regaining original shape after deformation: rheology, deformation, flow.
Strength	Specification of compressibility strength in psi.
Hardness/abrasiveness	Scratch and indentation hardness by Vickers hardness number: abrasiveness of coal
Friability	Ability to withstand degradation in size on handling, tendency toward breakage, two tests: tumbler test and drop shatter test.
Grindability	Relative amount of work needed to pulverize coal against a standard, measured by Hardgrove grindability index.
Dustiness index	Dust produced when coal is handled in a standard manner: index of dutiness
Thermal properties	
Calorific value	Indication of energy content in coal.
Heat capacity	Heat required to raise the temperature of a unit amount of coal by 1°.
Thermal conductivity	Rate of heat transfer through unit area, unit thickness, unit temperature difference.
Plastic/agglutinating	Changes in a coal upon heating and caking properties of coal, measured by Gieseler plastometer test.
Agglomerating index	Grading based on nature of residue from 1 g sample when heated at 950°C: Roga index
Free-swelling index	Measure of the increase in volume when a coal is heated without restriction, indication of plastic and caking properties.
Electrical properties	
Electrical resistivity	Electrical resistivity of coal in ohm-cm, coal is considered a semiconductor.
Dielectric constant	Electrostatic polarizability, related to the π electrons of aromatic rings.
Magnetic susceptibility	Diamagnetic, paramagnetic and ferromagnetic characteristics of coal.
Ash properties	
Elemental analysis	Major elements found in coal ash, 90% of ash is made up of SiO_2, Al_2O_3, and Fe_2O_3.
Mineralogical analysis	Analysis of the mineral content in coal ash.

(Continued)

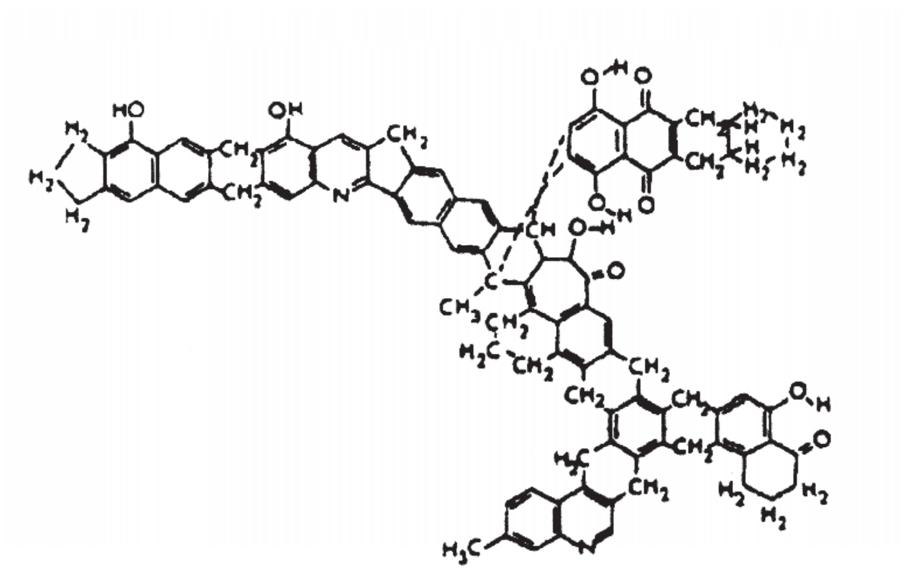
Table 6.9. (Continued)

Properties	Description of the analysis
Trace element analysis	Analysis of trace elements found in coal, 22 elements occur in most samples, averages show some enrichment in ash.
Ash fusibility	Temperature at which ash passes through defined stages of fusing and flow.
Petrographic properties	
Maceral composition	Specification of the maceral components of coal, important to describing how a coal will react in coal conversion and what coal products will be given off.
Vitrinite reflection	Important to maceral analysis and rank calculation
Sample information	
Sample history	Sampling date and agency, sample type.
Mine information	Mine life expectancy, reserves, annual production and mining method.
Sample location	Country, state, county, township, city, coal, province, and region.
Seam information	Age of seam, group, formation and seam thickness.

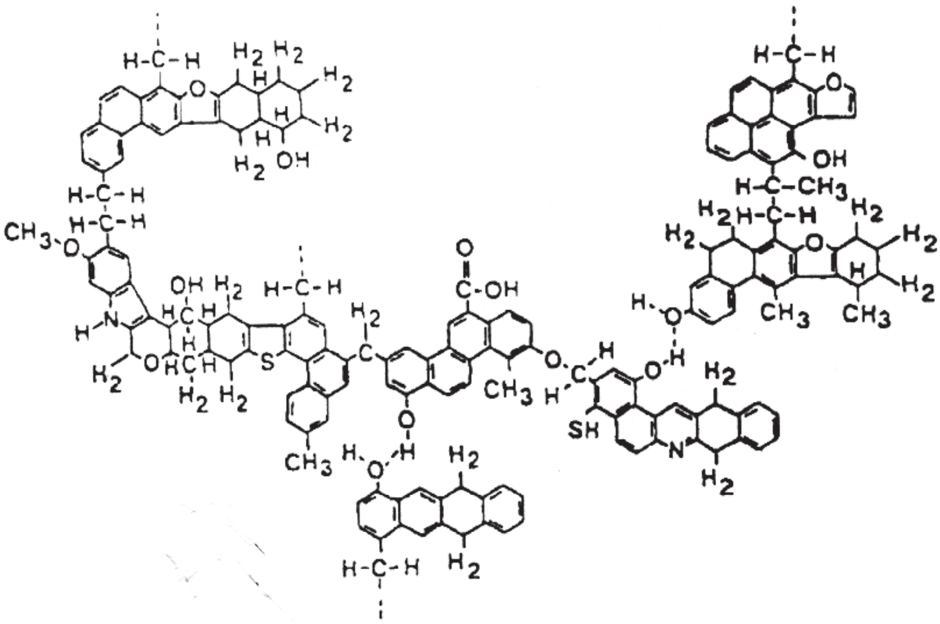
Source: Reference [54].

6.5 Coal Structure

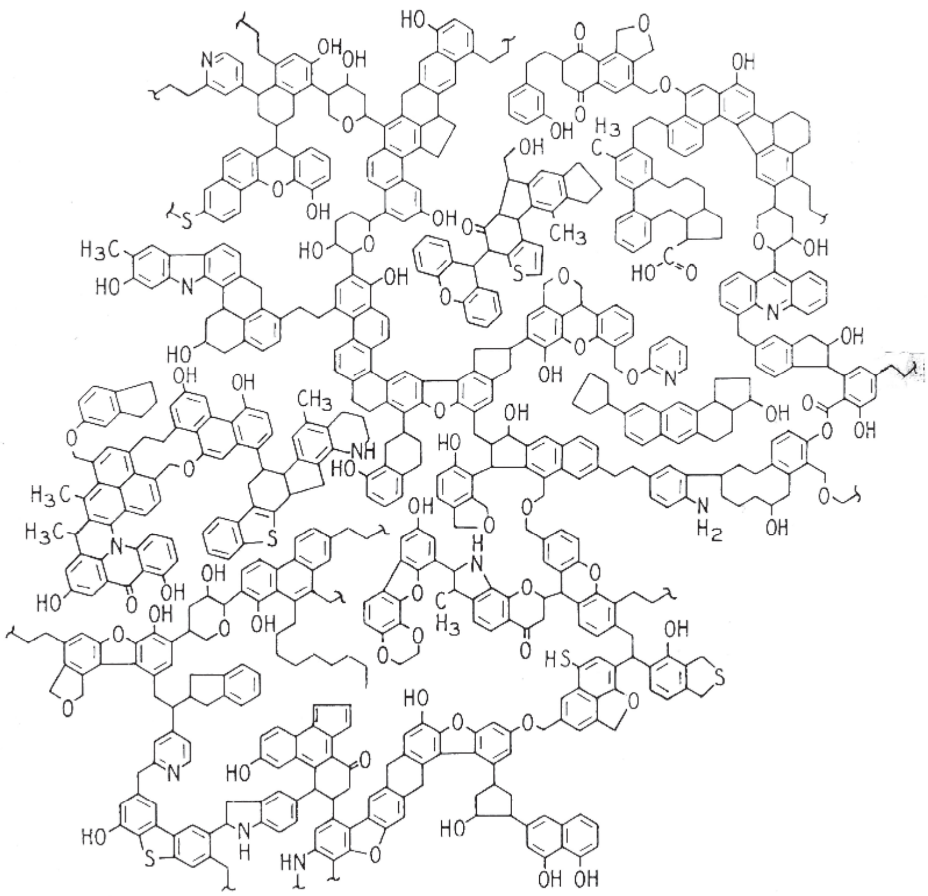
The structure of coal is extremely complex and depends on the origin, history, age, and rank of the coal. The molecular (chemical) and conformational structures of coal are studied to determine its reactivity during combustion, pyrolysis, and liquefaction processes [55–120]. Structures were derived using data obtained from various analyses including coal atomic composition, analysis of product from chemical reactions, coal liquefaction, and pyrolysis. Molecular models derived by various researchers for bituminous coal are shown in Fig. 6.3. Carlson [58] studied the three dimensional structures of coal using computer simulation and further analyzed the structures suggested by Given [121], Solomon [122], Shinn [123], and Wiser [124].



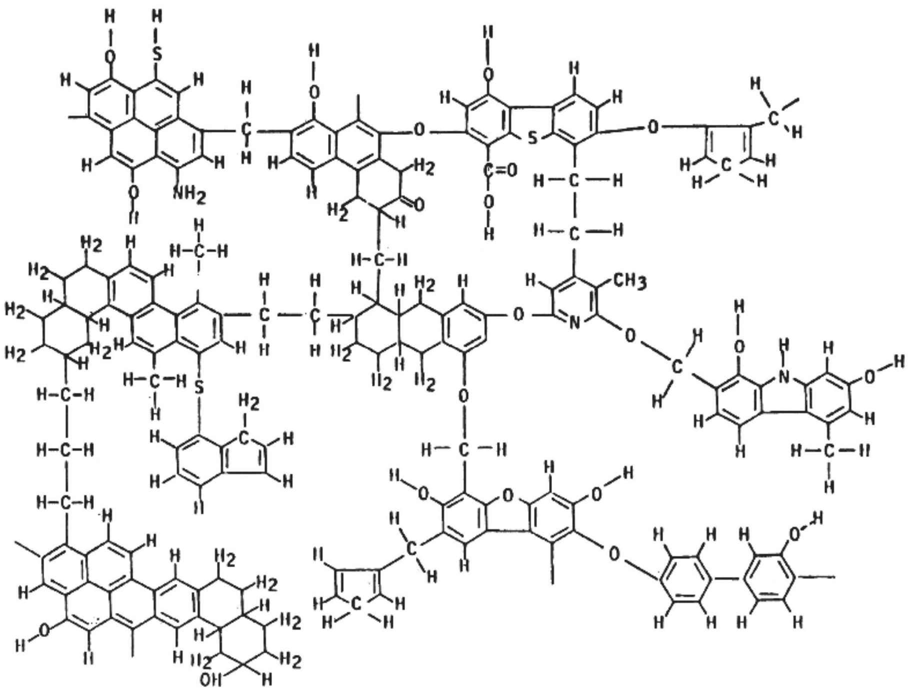
(a) Given [121]



(b) Solomon [122]



(c) Shinn [123]



(d) Wiser [124]

Fig. 6.3. Structures of coal as suggested by various researchers.

6.6 Coal Mining

The mining techniques used for extraction of coal depend on the quality, depth of the coal seam, and the geology of the coal deposit. The coal mining process can be classified into two categories depending on the mode of operation.

1. Surface Mining
   (a) Strip mining
   (b) Mountain top mining
2. Underground Mining
   (a) Room and Pillar mining
   (b) Longwall mining

A schematic depiction and various terminology associated with coal mining is given in Fig. 6.4.

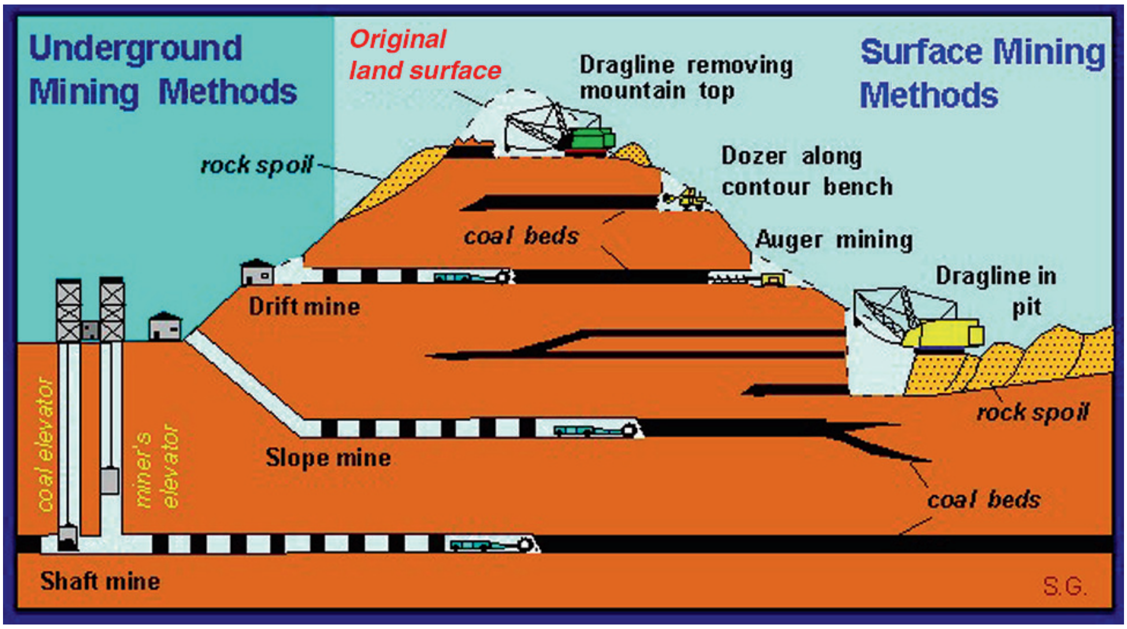


Fig. 6.4. A Schematic depiction of the range of different surface and underground types of coal mining, illustrating types of access to coal deposits and mining terminology [125].

6.6.1 Surface Mining

Surface mining is the most common type of mining of coal in the world. It is called strip mining. It accounts for around 80% of production in Australia, while in the USA it is used for about 67% of production. It is similar to open-pit mining in many regards. Surface mining is used when a coal seam is usually within 200 feet of the surface. The layer of soil and rock covering the coal (called the "overburden") is first removed from the surface to expose the coal, but is stored near the site

(Fig. 6.5). A variety of heavy equipment including draglines, power shovels, bulldozers, and front-end loaders are used to expose the coal seam for mining. After the surface mining, the overburden is replaced; it is graded, covered with topsoil, fertilized and seeded to make the land useful again for crops, wildlife, recreation, or commercial development. About 32% of coal in the USA can be extracted by surface mining, and about 63% of all U.S. coal is mined using this method today. Surface mining is typically much cheaper than underground mining.

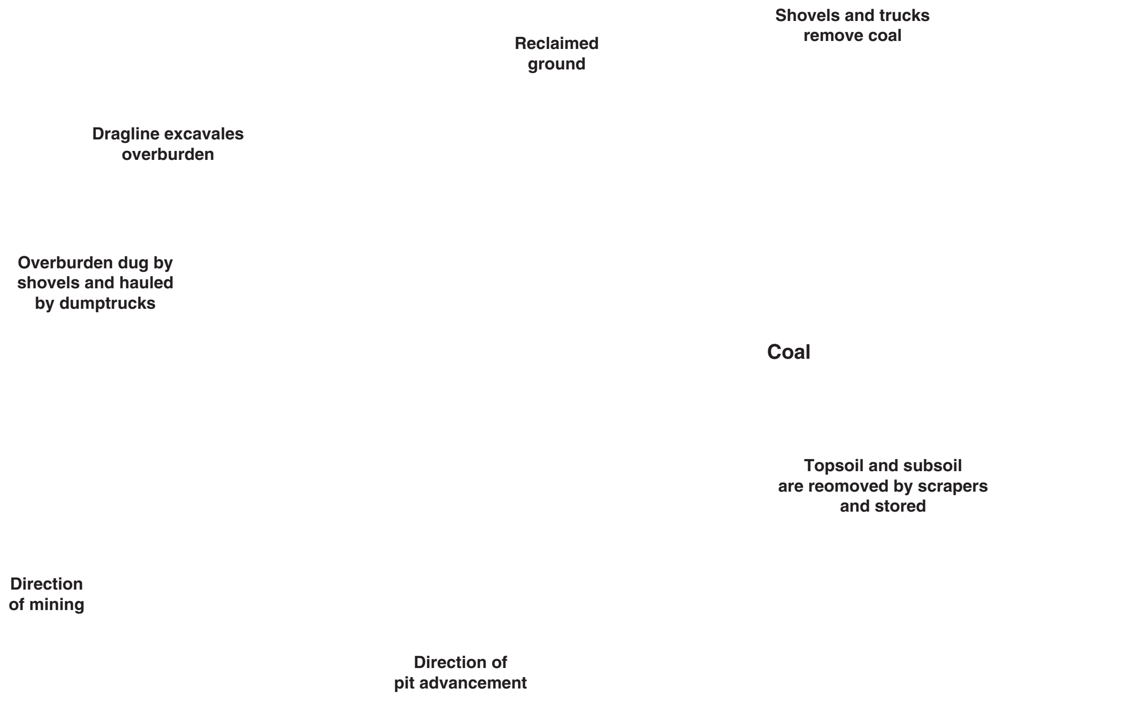


Fig.6.5. A schematic representation of surface mining. (Adapted from [126]).

Another type of surface mining is called mountain top mining. This type of mining is a relatively new process for coal mining from a depth of about 1,000 ft below the surface. In this process, the land is first clear-cut and then leveled by explosives. Dozens of seams are exposed on a single mountain by the blasts, lowering the mountain's height each time, sometimes by hundreds of feet [127]. Most mountain top mining in the United States occurs in West Virginia and Eastern Kentucky, and together they use more than 1,000 t of explosives per day for surface mining [128].

6.6.2 Underground Mining

Underground mining is used when the coal seam is several hundred feet below the surface. A vertical "shaft" or a slanted tunnel is constructed, called a "slope", to get the machinery and people down to the mine. Mine shafts may be as much as 1,000 ft deep.

6.6.2.1 Room and Pillar Mining

In room-and-pillar mining, a significant amount of coal is left behind to support the mine's roofs and walls (Fig. 6.6). Sometimes, this amount could be as much as half of the coal mined. Large column formations are necessary to keep the mine from collapsing. In this method, a set of entries, usually between 3 and 8, are driven into a block of coal. These entries are connected by cross-cuts, which are usually at right angle to the entries. The entries are commonly spaced from 50 to 100 ft apart, and the cross cuts are usually about 50–150 ft apart.

In the conventional room and pillar method, several operations known as undercutting, drilling, blasting, loading and roof bolting operations are performed to get to the coal. Recent advancement includes continuous room and pillar method that eliminates undercutting, drilling and blasting. The cutting and loading functions are performed by a mechanical machine – the continuous miner. The coal is loaded onto coal transport vehicles and then dumped onto a panel-belt conveyor for further transport out of the mine. Once the coal has been cut, the strata above the excavated coal seam are supported by roof bolts.

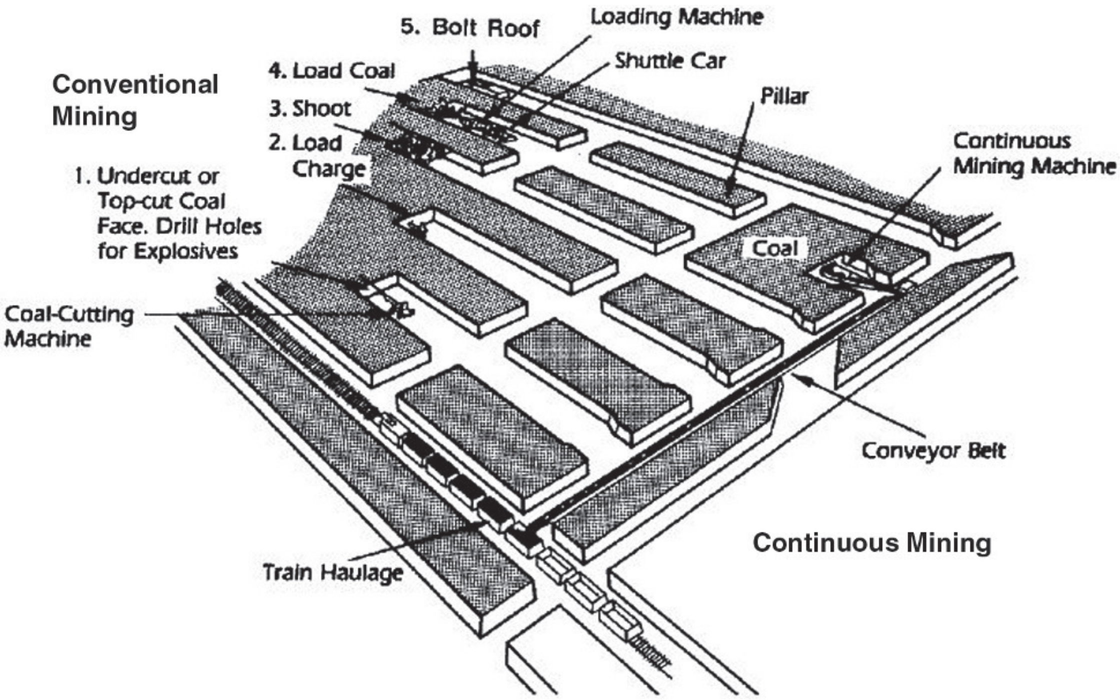


Fig.6.6. A schematic representation of room and pillar mining. (Adapted from [129]).

6.6.2.2 Longwall Mining

In this method, a mined-out area is allowed to collapse in a controlled manner (EIA [130]). Huge blocks of coal, up to several hundred feet wide, can be removed and high recovery and extraction rates are feasible (Fig. 6.7). However, the coal bed should be relatively flat-lying, thick, and uniform. The block of coal is further cut into small pieces using a high-powered cutting machine (the shearer). The sheared, broken coal is continuously hauled away by a floor-level conveyor system.

The use of longwall mining in underground production has been growing in the USA both in terms of amount and percentages, increasing from less than 10% of underground production (less than 10 million annual tons) in the late 1960s, to about 50% of underground production (over 200 million annual tons).

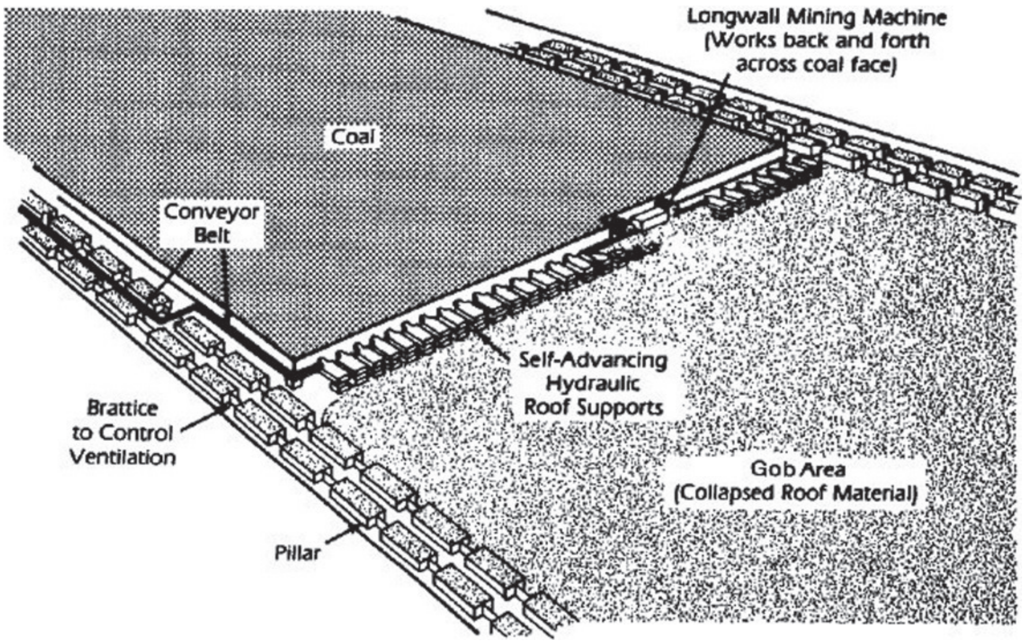


Fig. 6.7. A schematic representation of logwall mining. (Adapted from [131]).

Underground mining currently accounts for about 60% of world coal production, although in several important coal producing countries surface mining is more common.

6.7 Cost of Coal and Its Mining

A number of costs are associated with coal mining and its delivery price. The mining of coal involves various types of costs. However, with the use of modern and more efficient equipment, the cost of mining has gone down significantly. Some of the activities that are associated with the cost of coal mining include restoration of the land, mine drainage, and water usage. All these factors determine the cost of coal that is delivered to end users. The average price of coal at various regions in the USA and the price to the end users are given in Table 6.10.

The production cost of coal depends on the method of mining and also varies from region to region. In Table 6.11 is shown the cost of coal at various states in the USA for different mining methods.

Table 6.10. Average price of coal delivered to end use sector by census division and state, 2005, 2004 (dollars per short ton).

Census division and state	2005			2004			Annual percent change		
	Electric utility plants	Other industrial plants	Coke Plants	Electric utility plants	Other industrial plants	Coke plants	Electric utility plants	Other industrial plants	Coke plants
New England	65.39	85.57	–	52.14	65.54	–	25.40	30.60	–
Middle Atlantic	51.97	W	W	42.92	W	W	21.10	15.60	28.5
East North Central	30.45	53.89	89.97	26.69	41.22	63.30	14.10	30.70	42.1
West North Central	16.47	24.00	–	15.34	21.93	–	7.40	9.50	–
South Atlantic	51.21	W	W	43.29	W	W	18.30	25.60	36.8
East South Central	36.91	W	W	32.22	W	59.16	14.60	28.80	W
West South Central	21.55	W	–	20.72	W	–	4.00	12.70	–
Mountain	23.30	35.93	–	21.87	31.92	–	6.50	12.60	–
Pacific	21.33	50.62	–	19.91	42.94	–	7.10	17.90	–
US Total	31.22	47.63	83.79	27.30	39.30	61.50	14.40	21.20	36.2

W = Withheld to avoid disclosure of individual company data.

Includes manufacturing plants only.

Source: References [132–134].

Table 6.11. Average open market sales price of coal by state and underground mining method, 2005 (Dollars per short ton).

Coal producing state	Continuous[a]	Conventional[b]	Longwall[c]	Other[d]	Total
Alabama	W	–	W	–	54.75
Colorado	W	–	W	–	21.69
Illinois	W	–	W	–	29.18
Indiana	33.17	–	–	–	33.17
Kentucky Total	W	38.71	W	–	38.70
Eastern	W	W	W	–	43.55
Western	W	W	–	–	27.48
Maryland	W	–	–	–	W
Montana	W	–	–	–	W
New Mexico	–	–	W	–	W
Ohio	W	–	W	–	25.25
Oklahoma	W	–	–	–	W
Pennsylvania Total	46.07	40.17	W	W	36.23
Anthracite	W	W	–	W	46.74
Bituminous	W	W	W	–	36.18
Tennessee	49.89	–	–	–	49.89
Utah	25.17	–	21.02	–	21.45
Virginia	42.47	63.89	W	–	48.01
West Virginia Total	46.54	W	W	–	41.99
Northern	31.88	W	32.60	–	32.52
Southern	47.85	–	53.00	–	49.06
Wyoming	–	–	–	–	–
U.S. Total	**39.04**	**W**	**33.90**	**W**	**36.42**

[a]Mines that produce greater than 50% of their coal by continuous mining methods.

[b]Mines that produce greater than 50% of their coal by conventional mining methods.

[c]Mines that have any production from longwall mining method. A typical longwall mining operation uses 80% longwall mining and 20% continuous mining.

[d]Mines that produce coal using shortwall, scoop loading, hand loading, or other mining methods, or a 50/50% percent conventional/conventional split in mining method.

W = Withheld to avoid disclosure of individual company data.

Open market includes all coal sold on the open market to other coal companies or consumers. An average open market sales price is calculated by dividing the total free on board (f.o.b) rail/barge value of the open market coal sold by the total open market coal sold. Excludes mines producing less than 10,000 short tons, which are not required to provide data. Excludes silt, culm, refuse bank, slurry dam, and dredge operations. Totals may not equal sum of components because of independent rounding.

Source: References [135, 136].

Cost of coal is also different in different countries, particularly for the coal importers. In this case, the cost includes that of raw materials, insurance and freight. The cost in US dollar for Europe and Japan is given in Table 6.12.

Table 6.12. Coal price in other countries.

US dollars per tonne	Northwest Europe marker price †	US Central Appalachian coal spot price index[a]	Japan coking coal import cif price	Japan steam coal import cif price
1987	31.30	–	53.44	41.28
1988	39.94	–	55.06	42.47
1989	42.08	–	58.68	48.86
1990	43.48	31.59	60.54	50.81
1991	42.80	29.01	60.45	50.30
1992	38.53	28.53	57.82	48.45
1993	33.68	29.85	55.26	45.71
1994	37.18	31.72	51.77	43.66
1995	44.50	27.01	54.47	47.58
1996	41.25	29.86	56.68	49.54
1997	38.92	29.76	55.51	45.53
1998	32.00	31.00	50.76	40.51
1999	28.79	31.29	42.83	35.74
2000	35.99	29.90	39.69	34.58
2001	39.29	49.74	41.33	37.96
2002	31.65	32.95	42.01	36.90
2003	42.52	38.48	41.57	34.74
2004	71.90	64.33	60.96	51.34
2005	61.07	70.14	89.33	62.91
2006	63.67	62.98	93.46	63.04

[a]Price is for CAPP 12,500 BTU, 1.2 SO2 coal, fob.

cif = cost + insurance + freight (average prices); fob = free on board.

Source: Reference [137].

6.8 Transportation of Coal

The electric power sector uses more than 90% of the coal produced in the United States and is transported to more than 400 coal-burning power plant sites. About 58% of coal is transported by rail, 17% by water-ways, 10% by trucks, 3% are mine mouth plants with conveyor systems and the rest 12% by other methods (This includes barge) [138, 139]. However, these numbers do not include mode of transportation of coals to main transportation ports. The EIA figures report methods by which coals are delivered to its final destination (see Table 6.13), and do not describe how many tons may have traveled by other means along the way – almost one third of all coal delivered to power plants is subject to at least one trans-loading along the transportation chain [138]. For example, the U.S. Army Corps of Engineers reported that 223 million tons of domestic coal and coke were carried by water at some point in the transport chain in 2004 [140].

Recently transportation of coal as a slurry through pipelines has been explored. This type of transportation method not only requires water for transportation, but also need a number of pumping station to boost the pressure in the pipeline. It requires about 1 ton of water for 1 ton of coal and a booster pump for every 100 km when flowing at a velocity of 1–2 m/s.

Table 6.13. Mode of transportation of coal to end users (thousands short tons).

Delivery methods	Electricity generation	Coke plant	Industrial (except coal)[a]	Residential/ commercial	Total
Great Lakes	8,644	1,144	1,341	–	11,128
Railroad	625,830	10,414	46,031	1,975	684,249
River	71,062	3,722	7,915	406	83,105
Tidewater Piers	3,391	–	530	–	3,936
Tramway, Conveyor and Slurry Pipeline	79,997	1,014	31,975	–	115,262
Truck	73,441	453	50,266	2,741	128,900
Others	–	–	–	–	28,005
Total	863,802	17,095	150,309	5,122	1,064,348

[a] This category includes coal that is transported to plants that transform it into ‘synthetic’ coal that is then distributed to the final end-user – a substantial component goes to electricity generation plants.

Source: Reference [139].

6.9 Coal Cleaning

The objectives of coal cleaning are to remove ash, rock, and moisture from coal to reduce transportation costs and improve the power plant efficiency. Coal cleaning is now also focused on removing sulfur to reduce acid-rain-related emissions. The benefits of coal cleaning are: