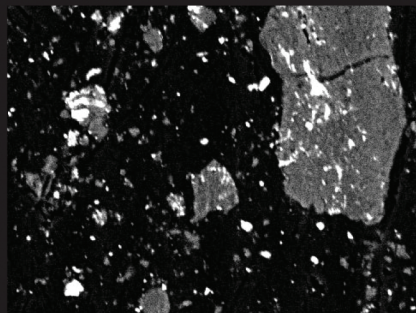


COAL PRODUCTION AND PROCESSING TECHNOLOGY



edited by
M.R. Riazi
Rajender Gupta



CRC Press
Taylor & Francis Group

**COAL
PRODUCTION
AND PROCESSING
TECHNOLOGY**

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Dedication

*To Shiva, Touraj, and Nazly
and
Rekha, Richa, and Raveen*

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Preface

Coal has been used as the most abundant and widely distributed source of energy for centuries and presently provides about 30% of the world's energy, second after oil. Coal alone provides 40% of current global electricity needs. The cost of electricity produced from coal is less than that produced from any other energy source. A significant proportion of coal is used for metallurgical processes. According to the International Energy Agency, in the twenty-first century, coal has been the fastest growing energy source; between 2000 and 2012 coal consumption increased by 60%, an average of 4% per year. For example, Japan announced the building of seven new coal-fired power plants in early 2015 to make up for the loss of power generation from nuclear plants. The main producers of coal are China, the United States, India, Australia, Indonesia, Russia, and South Africa, while the main importers of coal are China, Japan, South Korea, India, and Taiwan. While China produces 46% of the world's coal, it consumes more than 49% of global coal production.

Coal is a combustible solid organic rock, which is mainly composed of carbon, along with other elements such as hydrogen, oxygen, sulfur, and nitrogen. However, there are always some ash-forming minerals, such as quartz, clays, pyrites, and carbonates consisting of silicon, aluminum, iron, calcium, magnesium, sodium, potassium, sulfur, and phosphorus, responsible for almost all the operational and environmental issues in coal utilization. There are also some toxic trace elements, such as mercury, selenium, chromium, and antimony as well as some valuable elements such as germanium, gallium, uranium, molybdenum, and beryllium, which may also be present as traces in a coal sample.

Excessive use of coal has led to the utilization of low grade coals with higher mineral, sulfur, and moisture content, resulting in higher emissions of SO_x , NO_x , and trace elements apart from increased operational problems related to corrosion, erosion, and ash deposition. The biggest challenge related to coal has been greenhouse gas emissions, either as coalbed methane or as carbon dioxide in flue gas from combustion. Coal bed methane is currently a source of power. Carbon capture and storage is the most promising technique to reduce carbon

dioxide emission from coal combustion; research in this area is growing.

It was due to the above-mentioned importance of coal as a source of energy and associated issues in its utilization that led us to preparing this book. The present book is the result of more than two years of collective effort with contributions from more than 40 scientists and experts around the globe. The book has 23 chapters and is divided into 4 sections: Section I: Coal Reserves and Characterization of Coal, Section II: Coal Mining and Production, Section III: Coal Conversion Processes, and Section IV: Global Issues and Trends. Section II includes a chapter on coal bed methane, whereas Section IV includes a chapter on carbon capture and storage, a chapter on evaluation of coal companies, and a chapter on future trends in coal technologies. Although we attempted to cover all aspects of coal production and processing, this proved to be a difficult task, in which some topics have received less attention than they deserve. Readers may find some minor overlaps between the chapters; each chapter focuses on a unique topic specific to that chapter.

We are grateful to a number of experts who helped us in reviewing some chapters with their constructive comments and suggestions. Among them we are particularly indebted to Peter Cain, T. K. Das, Bulent Erdem, John R. Grace, Cigdem Keles, Allan Kolkler, Paul M. Mathias, Sachin K. Sharma, Luis Silva, Robert Sutherland and Deepak Pudasainee. We are also thankful to Taylor & Francis Group for publication of this book and in particular to Allison Shatkin, the managing editor, who was helpful in every stage of this project; her initial contacts and encouragement were instrumental in taking such a major task. We appreciate the work of Ashley Weinstein, project coordinator at CRC Press, who reviewed and edited this manuscript.

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Rajender Gupta, PhD, is a professor of chemical and materials engineering at the University of Alberta. He graduated in 1972 from IIT Kharagpur and earned a PhD at the University of Newcastle. He has been researching in the general area of clean coal technologies for well over 35 years. He has published more than 250 technical and research

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Dr. Gupta, before his current tenure at the University of Alberta, led several research projects at the Co-operative Research Centre for Coal in Sustainable Development at the University of Newcastle, Australia, on advanced coal characterization, mineral-to-ash transformation, and the performance prediction of coal-fired boilers.

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Section I

Coal Reserves and Their Characteristics

1 Nature and Chemistry of Coal and Its Products

Binoy K. Saikia, Ananya Saikia, and Bimala P. Baruah

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Abstract: Coal, a non-renewable resource, is far more plentiful than oil or gas with considerable amount of coal reserves worldwide. Coal and coal products play an important role in fulfilling the energy needs of the society. Basic knowledge about coal, its origin, and its formation will help in its future applications in power generation, metal processing, and chemical production. The greatest coal-forming period in geological history is during the Carboniferous era, while large deposits during the Permian,

with lesser but still significant in the Triassic and Jurassic periods, and minor in Cretaceous. The formation of coal has been explained either by in situ or by drift origin of vegetable matter under different conditions. The continuing effects of temperature and pressure over millions of years progressively increased the maturity of coal formation, that is, from peat to anthracite. The process of coalification starts with the biochemical process of peatification/humification followed by geochemical process. The types

of coal have been defined based on lithotypes, coal ranks, microlithotypes, and maceral contents. In this chapter, the chemical nature of coal and its products are summarized. It includes discussion on coal formation, types and nature of coals, coal ranks and classification, micro-constituents of coal, chemical composition of coal, heteroatoms in coal, coal chemical structure including molecular structure, analytical methods for coal characterization, rock types and mineral matters in coal, coal sampling (in situ and ex situ), coal analysis, elemental analysis of coal (C, H, N, O, Cl, Hg, etc.), analytical methods for coal analysis, coal products, chemical compositions of coal liquids, and other coal-derived products. The maceral composition, heteroatoms, mineralogy, and the presence of trace elements and rare earth elements in coals found in the different parts of the world are also reported. Emphasis is also given on X-ray diffraction technique for the structural characterization on coals, evaluation of the carbon stacking structure, estimating the size of the aromatic lamellae and the average distance between lamellae, and the mean bond distance. The contents of this chapter will be basically of help to the beginners and the coal fraternity in developing and designing advanced coal conversion technologies. Moreover, this chapter will serve as a basis for going through the subsequent chapters in the book.

1.1 INTRODUCTION

Coal is one of the abundant fossil fuels in most parts of the world. The largest coal reserves of the world are found in the United States (237,295 mt), Russia (157,010 mt), China (114,500 mt), Australia (76,400 mt), and India (60,600 mt) as on 2011 (World Energy Council 2013). Coal now becomes globally important in generating electricity, which could remain so for the next 200 years. It is a heterogeneous combustible sedimentary rock, which is mainly composed of carbon, hydrogen, and oxygen. It also contains other elements such as nitrogen, sulfur, and traces of mineral matter. This is the most plentiful resource of conventional energy, and it forms the backbone of the modern industrial civilization. Coal is also a source material for producing a wide range of chemicals, fertilizers, and liquid fuels. It currently provides 29.9% of the global primary energy needs and generates 41% of the world's electricity. Thus, coal is considered as the first source for electricity generation after oil and is considered to be the second source of primary energy in the world. However, the efficiency and sustainability of the processes utilized for processing of this resource will depend on an adequate, as well as advance, knowledge on the nature and chemistry of the coals (Saikia and Baruah 2008; Saikia et al. 2007a, b, c, 2009a, b, c). It is to be mentioned that coal appears black and rather homogenous at first sight; however, it consists of a heterogeneous type of chemistry.

1.2 ORIGIN AND FORMATION OF COAL

Coal originates from the prehistoric accumulation of vegetation in swamps and peat bogs followed by an aggregation of

heterogeneous materials composed of organic materials with some amount of moisture and inorganic mineral matters. Two main theories have been proposed to explain the origin and formation of coal. The first theory, which supposes growth-in-place of vegetable material, is called the *autochthonous theory*. It stated that the plants that compose the coal were accumulated in large freshwater swamps or peat bogs during many thousands of years. The second theory suggests that coal strata accumulated from plants, which had been rapidly transported and deposited under flood conditions afterward covered with sediments such as sands or clays. It claims transportation of vegetable debris and is called as the *allochthonous theory*.

In general, the formation of the coal can be attributed to the accumulation and preservation of plant remains in some areas of the earth where favorable climate prevails for the luxuriant growth of flora (see Figure 1.1). Different coals undergo different degrees of chemical and physical alteration of the parent organic debris under different temperature and pressure conditions. Peat is the precursor of coal, and is formed in the first phases. The formation of peat is controlled by several factors, including: (1) the evolutionary development of plant life and (2) the physical conditions of the area. Warm and moist climates are thought to produce broad bands of bright coal. Cooler and temperate climate, on the other hand, are thought to produce dirty coal with relatively little brightness.

The whole process of coal formation from such type of plant materials is a very complex and a long-term process, which involves physical, chemical, and biochemical reactions. Thus, the nature and chemistry of coal depend upon the properties of different constituents present in the mass of plants and vegetables, the nature and extent of the changes on which these

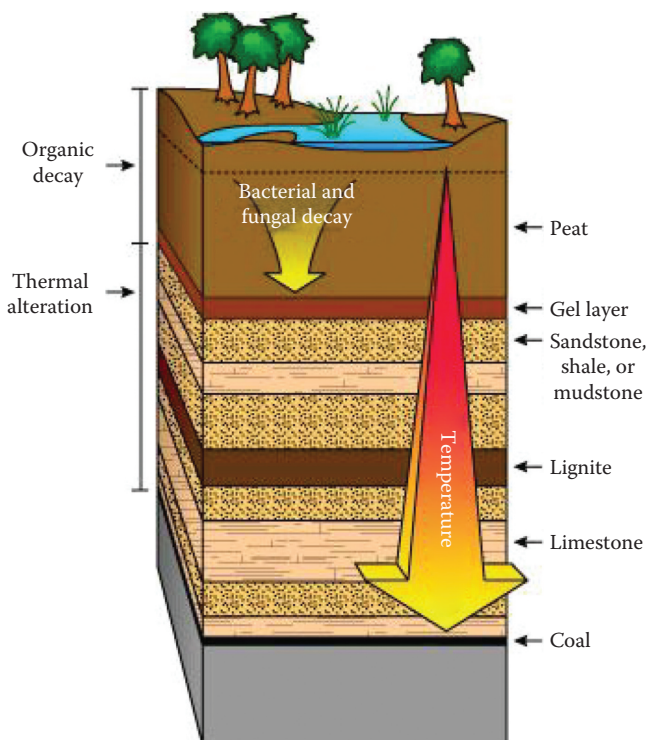


FIGURE 1.1 Schematic view of the general process of coal formation.

constituents have undergone since their deposition, as well as the nature and quantity of the inorganic matter present. This process is commonly called as *coalification*. The general sequence of coalification is from lignite to sub-bituminous to bituminous to anthracite. The process of coalification starts with the biochemical process of peatification of the dead plant materials. It is continued initially biochemically and then as a very complex geochemical process when peatification has ceased and the peat has been covered with other sediments. Depending upon the degree of coalification, different types of coal are formed. The main factors that are decisive for the coalification are primarily time, pressure, and temperature.

In the biochemical stage, the plant materials are decomposed and degraded under atmospheric oxidation by fungi and aerobic bacteria, which are further transformed into coal micro-constituents under the main controlling factors such as hydrogen-ion (pH) concentration and redox potential (Eh) of the medium (Chandra et al. 2000). With increased burial, bacteriological activity ceases and is considered absent at depths greater than 10 m (Stach et al. 1982). The quality of the coal produced also depends on the nature and extent of the decomposition and degradation of the plant material. The thickness of the coal seams can be determined from the rate of accumulation and subsidence of the coal-forming basins. Slower subsidence and greater accumulation of plant materials leads to greater thickness of coal seams. The coal formation is also related to the tectonic disturbances, which in turn help in the transformation by bringing sufficient overburden pressure and temperature gradient required for the coal generation. The geochemical or metamorphic stage of the coalification process involves progressive changes through increase in carbon content and decrease in the hydrogen and oxygen contents, resulting in a loss of volatiles within the coal. This, together with continued water loss and compaction, results in the reduction of the coal volume. There is reduction in moisture content and increase in methane-to-carbon dioxide ratio with the increase of coal rank. These changes in the physical and chemical properties of the coal are in reality the changes to the inherent coal constituents during coalification. The optically homogeneous discrete organic material in coal called as *macerals* are produced during peatification and coalification, while the inorganic materials consist primarily of mineral matter, chiefly clay minerals, quartz, carbonates, sulfides, and sulfates; many other matters in very small quantities were accumulated as well (Ting 1982). The total bulk of inorganic constituents present in coal ranges from a few percent to more than 50%. If the inorganic constituent is >50 wt%, it is classified as *carbonaceous shale*. Schopf (1956) has classified aggregates containing organic material amounting to >50 wt% and >70 vol.% as coal (Ting 1982). In a coalification process, the degradation of peat occurs through complex chemical reactions and through the activity of microorganisms. As peat formation and coalification proceeds, living biomass, which have more or less open structures, are broken down, and new compounds, primarily aromatic and hydro-aromatic, are produced. These compounds are connected by cross-linked oxygen, sulfur, and other functional groups such as methylene. However, the initial chemical changes of vegetable matters in the coalification process

have been debated since the beginning of this century, with a cellulose theory and a lignin theory (Ghosh and Prelas 2009). A number of researchers concluded that the cellulose in plants was the main path toward the ultimate formation of the coal. Both the theories have been reviewed and their applicability to various deposits of the world had been discussed. However, it was concluded that a single theory could not be applied to explain these deposits (Ghosh and Prelas 2009).

Time is another important factor, which plays a significant role in coalification. It has been suggested that the process from accumulation to coal formation requires at least one million years (Chandra et al. 2000). According to the geologists, sufficient coal deposits were formed in the Upper Palaeozoic era ranging in age from 358.9 ± 0.4 to 252.2 ± 0.5 million years, particularly in the Carboniferous and Permian periods. The three major episodes of coal accumulation were established within the geological column from the Carboniferous to Quaternary periods (Figure 1.2). The first episode took place during the Late Carboniferous to Early Permian periods, where coals formed the bulk of the black coal reserves of the world. The coals formed during these periods are of high rank undergoing significant structural changes. These coal deposits extend across the Northern Hemisphere from Canada and the United States, through Europe and the Commonwealth of Independent States to the Far East. In the Southern Hemisphere, these Carboniferous–Permian coals of Gondwanaland are preserved in South America, Africa, the Indian subcontinent, Southeast Asia, Australasia, and Antarctica. The second episode occurred during the Jurassic–Cretaceous period and is present in Canada, the United States, China and the Commonwealth of Independent States (Russia included). The third major episode occurred during the Paleogene–Neogene periods, where coals formed are mainly lignite to anthracitic types. These coals form the bulk of the world's brown coal reserves. Paleogene–Neogene coals are also found worldwide, and are the focus of current exploration and production as the traditional Carboniferous coalfields become depleted or geologically too difficult to mine (Thomas 2013). The coal deposits found in Turkey are found to be of Oligo–Miocene in age in accordance with its fossil findings (Tozsın 2014).

1.3 TYPES OF COALS

Based on the macroscopically recognizable components termed as *lithotypes* (Stach et al. 1982), coals are divided into two main groups: sapropelic and humic coals. Sapropelic coals are derived from variety of microscopic plant debris such as resins, waxes, or fats under sub-oxic to anoxic conditions and have a homogeneous appearance. These coals are characteristically fine-grained, homogeneous, dark in color and display a marked conchoidal fracture (Thomas 2013). These deposits are usually lenticular in shape, local in extent, and occur at the top of a coal bed (Parks 1952). They may occur in association with humic coals or as individual coal layers. Humic coals are composed of a diversified mixture of macroscopic plant debris such as wood, bark, and leaves, deposited under oxic to sub-oxic conditions and they typically have a banded

that the coal undergoes during burial and tectonic effects and is assessed in terms of moisture and carbon content, volatile matter, and vitrinite reflectivity. The ranks of coals, from most to least carbon, are lignite, sub-bituminous, bituminous, and anthracite (Thomas 2013). Increasing rank is also accompanied by a rise in the carbon and energy contents and a decrease in the moisture content of the coal. According to Tissot and Welte (1984), the process of coalification occurs in three stages: diagenesis, catagenesis, and metagenesis. In the diagenetic stage, coals formed include peat, lignite (A and B), and sub-bituminous (C and B), which are formed by compaction, loading, and chemical transformation due to bacterial activity and temperature. The lignite and bituminous coals were further divided into A, B, C, and D levels under *American Society for Testing and Materials* (ASTM) classification based on decreasing heating value on moisture mineral matter free basis. The coals formed within catagenetic stage are sub-bituminous A and high-, medium-, low-volatile bituminous, which are formed through the effects of heat, pressure, and time, whereas at the metagenetic stage, semi-anthracite, and anthracite are formed by prolonged action of temperature and pressure.

The basic rank progression of coals is summarized in the Table 1.1. The extent of peatification and coalification can be examined by using the Van Krevelen diagram (Figure 1.3). The loss of oxygen-containing functional groups during diagenesis can be clearly seen in the decreasing Oxygen/Carbon (O/C) ratios of the humic coal band, which is primarily attributable to the evolution of CO₂ and H₂O, while the Hydrogen/Carbon (H/C) changes very little (Killops and Killops 2013).

With increasing burial of the peat, chemical and physical changes occur. Due to compaction, the moisture content decreases and carbon content increases shown by decreasing atomic O/C ratios (Figure 1.3). And the carbon content continues to increase with increasing rank, while at the same time, the oxygen and hydrogen contents decrease.

1.4.2 CLASSIFICATION OF COAL

Due to variation in chemical composition and properties, coal is classified by variety of methodologies. The coalification process has an important bearing on its physical and chemical properties. A number of classification systems have been developed (Hawe-Grant 1993). On the basis of utilization in different fields, classification may be divided into two types: scientific and commercial. The scientific classifications are Regnault Grüner-Bone, Fraser, Seyler, ASTM, and National Coal Board classifications. The commercial classification comprises classification by grade.

1.4.2.1 Scientific Classifications

1.4.2.1.1 Regnault Grüner-Bone Classification

The Regnault Grüner-Bone classification is based on the elemental composition of coal (C, H, O, N, and S), volatile matter contents, and caking nature of coals (Chandra et al. 2000).

1.4.2.1.2 Fraser Classification

Fraser classified coal on the basis of fuel ratio (fixed carbon/volatile matter) and divided into four groups: bituminous, semi-bituminous, semi-anthracite, and anthracite (Chandra et al. 2000).

TABLE 1.1
Characteristics of the Different Ranks of Coals

Rank (From Lowest to Highest)	Properties
Lignite	1. The lowest rank of coal that has been transformed into a brown-black coal from peat 2. Contains recognizable plant structures 3. Excessive moisture (25%–50%) 4. Heating value less than 8300 BTU/lb on a mineral matter free basis 5. Carbon content between 60% and 70% on a dry ash-free basis
Sub-bituminous	1. Denser and harder than lignite 2. Lower moisture content (12%–25%) 3. With higher carbon content (71%–77%) on dry ash-free basis 4. Heating value between 8300 and 13000 BTU/lb on mineral matter free basis 5. On the basis of heating value, it is subdivided into sub-bituminous A, sub-bituminous B, and sub-bituminous C ranks
Bituminous	1. Alternate bright and dull bandings 2. Harder and denser than sub-bituminous coal 3. Carbon content between 77% and 87% on dry ash-free basis 4. Heating value much higher than lignite or sub-bituminous coal 5. On the basis of volatile content, bituminous coals are subdivided into low volatile bituminous, medium volatile bituminous, and high volatile bituminous
Anthracite	1. Anthracite is the highest rank of coal 2. Carbon content over 87% on dry ash-free basis 3. Anthracite coal generally has the highest heating value per ton on a mineral matter free basis 4. It is often subdivided into semi-anthracite, anthracite, and meta-anthracite on the basis of carbon content

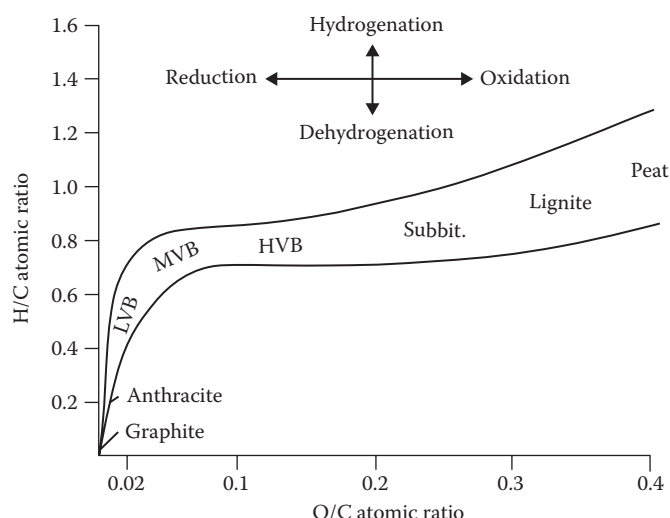


FIGURE 1.3 Van Krevelen diagram illustrating the range of H/C and O/C atomic ratios for various coalification stages. (Data from Van Krevelen, D.W., *Coal: Typology-Chemistry-Physics-Constitution*. Elsevier Science, Amsterdam, The Netherlands, 514, 1961; Langenberg, W. et al., *Coal Geology and Its Application to Coal Bed Methane Reservoirs. Lecture Notes for Short Course*, Information Series No. 109, Alberta Research Council, Alberta Geological Survey, Edmonton, 9, 1990.)

1.4.2.1.3 Seyler Classification

The Seyler classification is based on the carbon and hydrogen content of coals determined on dry mineral matter basis. In the scientific category, the Seyler chart method has considerable value. It gives the range and interrelationship of the properties of coal including parameters such as moisture content and swelling indices (Seyler 1938).

1.4.2.1.4 ASTM Classification

The ASTM classification system adopted in 1938 as a standard means of specification is used in the United States and in many other parts of the world, and is designated as D388 in ASTM standard. In this classification, the higher rank coals are specified by fixing carbon >69 wt%, or from volatile matter <31 wt%, on a dry mineral free basis. Lower rank coals are classified by calorific value (on moisture and mineral matter free basis).

1.4.2.1.5 National Coal Board Classification

This classification of coal proposed in 1946 by the UK Department of Scientific and Industrial Research. There are two parameters: the quantity of volatile matter determined on dry mineral matter free basis and the Gray-King coke-type assay, a measure of coking as designed in the British Standards. The Gray-King coke-type assay is used as a primary means of classification for lower rank coals having less than 10 wt% ash content.

1.4.2.1.6 Classification Based on Source of Genesi

This type of classification depends upon the character or the original vegetable matter. The different types are humic and sapropelic coals.

1.4.2.1.7 Classification by Rank

Classification by rank is made on the degree of the coalification, which gives an information about its carbon content with anthracite having the highest carbon content followed by bituminous, sub-bituminous, and lignite coal (in descending order). However, peat is not regarded as coal. Coalification or metamorphosis of coal results in changing of the physical and chemical properties of coal in response to temperature and time. With extreme metamorphism, anthracite can change to graphite (Chandra et al. 2000).

1.4.2.2 Commercial Classification

1.4.2.2.1 Classification by Grade

This classification is made on the basis of the proportion of impurities contained in coal. The extraneous matter forms most of the noncombustible impurities of coal. The classification of commercial grades of coals in India was evolved based on the ash contents, moisture, and calorific values (Chandra et al. 2000).

1.5 MICRO-CONSTITUENTS OF COAL

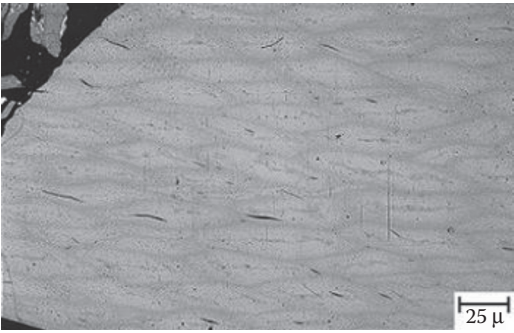
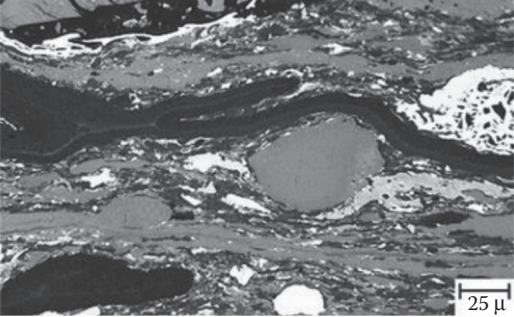
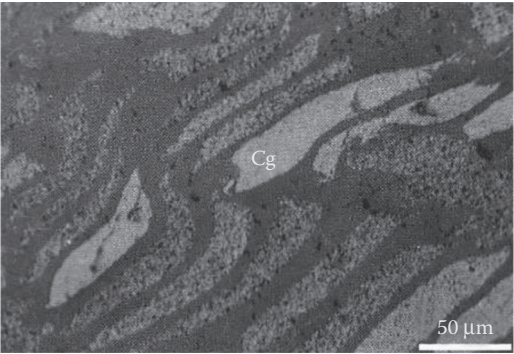
Coal is primarily composed of two parts: organic and inorganic. The micro-components and microstructures present in the organic part are called *macerals*, which are considered to be the building blocks of coal. There are three maceral groups known as *inertinite*, *liptinite* (formerly *exinite*), and *vitrinite* as shown in Table 1.2, along with their subgroup and photomicrographs. Inertinite is derived from the partial carbonization of the coal-forming materials by fire or intensive degradation by microorganisms. Vitrinite is derived from woody tissues of plants, which are chemically composed of the polymers, cellulose, and lignin. Vitrinite is the most abundant maceral in coal; however, most coals from Gondwanaland and some coals from western Canada are vitrinite poor. Exinite, also known as *liptinite*, is derived from waxy and resinous parts of plants such as spores, cuticles, and similar materials. This group is very sensitive to advanced coalification and it begins to disappear in medium-volatile-rank coals and are absent in coals of low-volatile rank. Vitrinite is the most important maceral in coals and is generally found to be the most abundant maceral in coals. However, inertinite and more rarely liptinite is the most abundant maceral group in some coals of Palaeozoic or Mesozoic age. The chemical composition of the three macerals is different. Liptinite macerals are more enriched in aliphatic hydrogen than vitrinite. The aliphatic CH and CH₂ carbon decrease in the order liptinite > vitrinite > inertinite in coals. Thus, the liptinites are distinguishable by a higher aliphatic (i.e., paraffin) fraction. Vitrinites contain more oxygen than the other macerals at any given rank level. In low-rank coals, the carbon atoms present in vitrinite are divided between aliphatic and aromatic bonding, but hydrogen occurs predominantly as aliphatic grouping. The aromaticity of the maceral groups increases with increasing rank. At low rank, in reflected white light, liptinite appears dark, vitrinite appears as a mesostasis of medium grey appearance, and inertinite has a higher reflectance than the other maceral groups. The

reflectance of vitrinite and inertinite converge within the semi-anthracite to anthracite range.

However, the bireflectance of vitrinite is much greater than that of inertinite except in the case of some contact-altered vitrinites and these two maceral groups can still be distinguished in plane-polarized light or with partially crossed polars (ICCP 2011). It is seen from the laboratory studies of coal

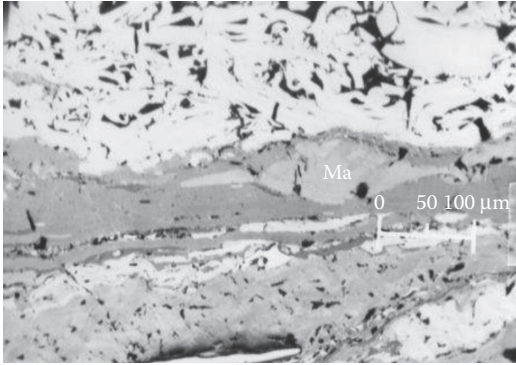
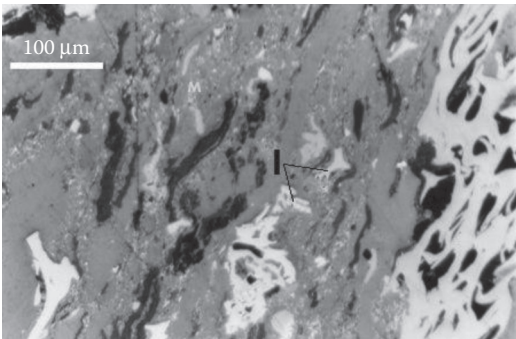
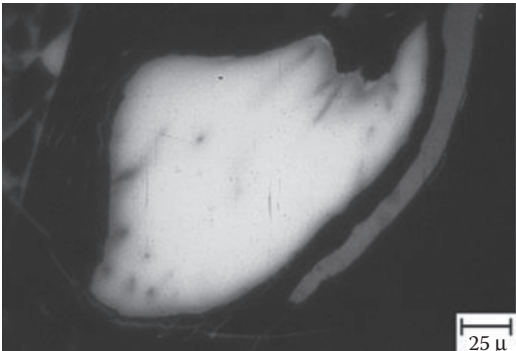
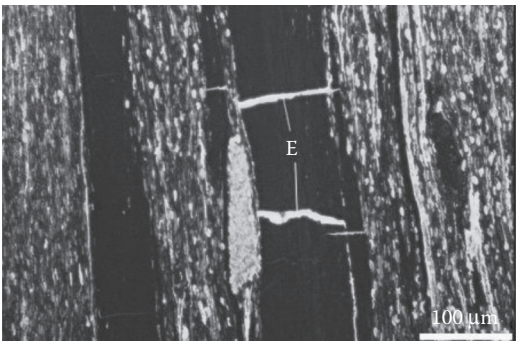
macerals carried worldwide that the coals in the United States and the United Kingdom are enriched in vitrinite and exinite, whereas coals from Southern Hemisphere, India, China, and those originating from Gondwanaland have inertinite as their dominant maceral (Sanyal 1997). The tertiary Indian coals are usually characterized by high vitrinite content (80% average), with the nonvitrinite fraction being predominantly inertinite,

TABLE 1.2
Maceral Groups, Subgroups, and Photomicrographs of Macerals of Coals

Maceral Group	Maceral Subgroup	Maceral	Photomicrographs
Vitrinite	Telovitrinite	Textinite Texto-ulminite Ulminite Collotelinite	
	Detrovitrinite	Attrinite Densinite Vitrodetrinite Collodetrinite Corpohuminite	
	Gelovitrinite	Corpogelinite Gelinite	
Inertinite	Macerals with plant cell structures	Fusinite Semifusinite Funginite	

(Continued)

TABLE 1.2 (Continued)
Maceral Groups, Subgroups, and Photomicrographs of Macerals of Coals

Maceral Group	Maceral Subgroup	Maceral	Photomicrographs
	Macerals lacking plant cell structures	Secretinite Macrinite Micrinite	
	Fragmental inertinite	Inertodetrinite	
Liptinite		Sporinite Cutinite Suberinite Resinite Fluorinite Liptodetrinite Alginite Bituminite	
	Strictly a bitumen rather than a maceral	Exsudatinite	

Source: ICCP, Organic petrology, macerals, microlithotypes, lithotypes, minerals, rank. Chapter 2. *Training Course on Dispersed Organic Matter*, Department of Geoscience, Portugal, 4–71, 2011.

which are low in proportions. The liptinite content is usually found to be less than 20% (Sharma et al. 2012). The Çardak coal deposits in south-western Turkey are characterized by the dominance of vitrinite, mainly huminite group (up to 92 vol.%, on mmf basis), followed by liptinite (up to 14 vol.%), and inertinite (up to 10 vol.%) (Oskay et al. 2013).

1.5.1 MICROLITHOTYPES

The term *microlithotype* is for the designation of rock types within coal that are at a microscopic scale. The definition is based on maceral percentages in coals. Thus, layers with >0.05 mm in thickness and consisting of more than 95% vitrinite are termed as *vitrite*. Bimaceral (clarite, durite, and vitrinertite) and trimaceral (duroclarite and clarodurite) microlithotypes are derived from lithotypes rather than macerals. In Palaeozoic coals, a wide range of microlithotypes, such as vitrite, clarite, durite, and inertite, can be present. Inertinite is present as durite in Carboniferous coals, whereas it is present as inertite in Gondwana coals. The

microlithotypes present in significant proportions in tertiary coals are vitrite and clarite (liptinite greater than 5% and inertinite less than 5%). Use of the microlithotype terms assists by indicating the ratio of telovitrinite (preferentially associated with vitrite) to detrovitrinite (preferentially associated with clarite) and the amount of liptinite present. However, these distinctions can commonly be made more directly by using maceral analyses (ICCP 2011). The classification of microlithotypes is shown in Table 1.3.

1.6 CHEMICAL COMPOSITION AND HETEROATOMS IN COAL

1.6.1 CHEMICAL COMPOSITION

The principal chemical constituents of coal are carbon, hydrogen, and oxygen with fewer amounts of nitrogen and sulfur. The chemical formula of coal may be approximated as $C_{135}H_{96}O_9NS$ (Raghuvanshi et al. 2006). With the increase of

TABLE 1.3
Microlithotypes of Coal

Maceral Composition (Mineral Free)	Microlithotype	Maceral Group Composition	Microlithotype Group
Monomaceral		Vitrinite > 95%	Vitrite
Collinite > 95%			
Telinite > 95%			
Vitrodetrinite > 95%			
Sporinite > 95%	Sporite	Exinite(liptinite) > 95%	Liptite
Cutinite > 95%	Algite		
Resinite > 95%			
Alginite > 95%			
Liptodetrinite > 95%			
Semifusinite > 95%	Semifusinite	Inertinite > 95%	Inertite
Fusinite > 95%	Fusinite		
Sclerotinite > 95%	Inertodetrinite		
Inertodetrinite > 95%	Macroite		
Macrinite > 95%			
Bimaceral	Sporoclarite	Vitrinite + exinite(liptinite) > 95%	Clarite
Vitrinite + sporinite > 95%	Cuticoclarite		
Vitrinite + cutinite > 95%			
Vitrinite + resinite > 95%			
Vitrinite + liptodetrinite > 95%			
Vitrinite + macrinite > 95%		Vitrinite + inertinite > 95%	Vitrinertite
Vitrinite + semifusinite > 95%			
Vitrinite + fusinite > 95%			
Vitrinite + sclerotinite > 95%			
Vitrinite + liptodetrinite > 95%			
Inertinite + sporinite > 95%	Sporodurite	Inertinite + exinite(liptinite) > 95%	Durite
Inertinite + cutinite > 95%			
Inertinite + resinite > 95%			
Inertinite + liptodetrinite > 95%			
Trimaceral	Duroclarite	Vitrinite > inertinite, exinite(liptinite)	Trimacerite
Vitrinite + inertinite + exinite > 5%	Vitrinertoliptite	Exinite > inertinite, vitrinite	
	Clarodurite	Inertinite > vitrinite, exinite(liptinite)	

Sources: ICCP, *International Handbook of Coal Petrology*, CNRS, Paris, France, 160, 1963; ICCP, *Supplement to Second Edition of the Handbook*, CNRS, Paris, France, 1971; ICCP, *International Handbook of Coal Petrology*, CNRS, Paris, France, 1975.

maturity of coal from lignite to anthracite, the carbon content increases, while the oxygen content decreases. The result is that the calorific value of coal increases with rank. Apart from these main constituents of coal, the presence of inorganic elements in coals from various coalfields of the world is also reported (Chandra et al. 2000; Saikia et al. 2009a, b, c). They include Ag, Al, As, Au, B, Ba, Be, C, Ca, Cd, Cl, Co, Cr, Cs, Cu, F, Fe, Ga, Ge, He, Hf, Hg, I, Br, In, K, Na, Li, Mg, Mn, Mo, Nb, Ni, P, Pb, Pt, Rh, Pd, Ra, Rb, Re, S, Sb, Cs, Se, Si, Sn, Sr, Ti, Th, Te, Ta, U, V, W, Y, La, Pr, Nd, Sm, Eu, Gd, Tb, Ho, Dy, Er, Yb, Lu, Zn, and Zr. Some of the elements present in coals are also identified as hazardous air pollutants in the 1990 Clean Air Act Amendments, United States. However, the amount of these inorganic elements in different coals widely varies with their different geochemical aspects. The determination of these elements in coals have been conducted by using X-ray photoelectron spectroscopy, neutron activation analysis, isotope dilution mass spectroscopy, spark source mass spectrometry, atomic absorption spectrometry, and other analytical techniques (Chandra et al. 2000; Ward 2002).

The inorganic matter present in coal may be divided into two groups of chemical elements: first group as the main or ash-forming elements [Si, Al, Fe, Ca, Mg, Na, K, Ti, (S, P)] and the second as the trace or rare elements, which usually increase after coal combustion and utilization. The trace elements include Cl, F, Hg, As, Se, and Cr along with rare elements such as Ge, Ga, U, Mo, Be, Sc, and rare earth elements. Some trace elements prove to be valuable (silver, zinc, and germanium), while some have the potential to be hazardous (cadmium and selenium) if their concentration is more than trace amounts (Yudovich and Ketris 2005). Significant concentration of trace elements such as Ge, Se, Cd, Cl, Co, As, Cr, Hg, Mn, Gd, Hf, Li, In, Nb, Ni, Sr, Ba, Th, and rare earth elements are found in high-sulfur coals of Russia (Yudovich and Ketris 2002). The trace elements such as As, B, Pb, Se, Cu, V, Ba, Ge, Mn, and Sn (Baruah et al. 2003) are found in coals of Assam, India. The coals in the United Kingdom have concentrations of As, which is significantly higher than worldwide average, while elements such as Zn are lower (Zandi and Russell 2004).

1.6.2 HETEROATOMS

The heteroatoms in coal is a very important aspect of coal structure and is extremely significant in coal conversion processes and design of catalysts for these processes (Speight 2013). The preliminary study on the presence or absence of functional groups of coal is performed by Fourier infrared spectroscopic analysis of coals. But, the recent advanced level studies and examination of the functional entities in coal have brought to light some interesting features the occurrence and distribution of the heteroatoms (Gupta 2006; Speight 2013). The assessment of the macromolecular structure of the nitrogen, sulfur, and oxygen heteroatom species in coal and coal-derived products is a complex and yet challenging analytical problem in coal chemistry. Oxygen occurs predominately as phenolic or etheric groups, with fewer amounts of carboxylic acids or esters and some carbonyls. Nitrogen occurs predominantly as pyridine or pyrrolic-type rings

in coal. Sulfur has similar chemistry to oxygen, and it also creates environmental problems during coal utilization.

1.6.2.1 Oxygen

Out of the three heteroatoms found in coal, oxygen has received the most important attention, and it is divided into four categories: (1) carboxyl, (2) carbonyl, (3) hydroxyl, and (4) ether, out of which only the first three categories are amenable to quantitative analysis. The ether bond in coal is mainly is of diaryl ($\text{Ar}-\text{O}-\text{Ar}$) and benzyl-aryl ($\text{C}_6\text{H}_5\text{CH}_2-\text{O}-\text{Ar}$) types, although methoxyl groups ($\text{CH}_3\text{O}-$) and dialkyl ethers ($\text{R}-\text{O}-\text{R}'$) are found in low-rank coals (Attar and Hedrickson 1982). The amount of oxygen in carboxylic groups decrease continually with the increase in coal rank until about 80% carbon, where the only oxygen groups present are phenolic and carbonyl groups. Aliphatic hydroxyl groups have been reported in brown coals. Thus, for coals of rank higher than lignites, oxygen can be accounted for as carbonyls, hydroxyl, or carboxyl with minor amount of heteronuclear oxygen, although there is now growing evidence for various ethers in coals. A great deal of information regarding the location of oxygen in coal structure has been derived from infrared spectroscopic investigations. The high-sulfur coals from northeast region of India were extensively studied by using Fourier transform infrared (FT-IR) spectroscopy and found to contain long aliphatic chains with parallel orientations (Baruah and Khare 2010; Saikia et al. 2007a, b, c, 2009a, b, c). The oxygen-containing functional groups found in these coals include phenols, alcohols, ethers, carboxylic acid, and carbonyls (Saikia et al. 2007a, b, c). However, the infrared spectroscopic data tend to suffer from their inability to be fully quantitative, and can be used to illustrate trends throughout the progression from low-rank coals to high-rank coals (see Table 1.4). A series of coals of varying rank, from brown coal to anthracite, of the Ordos Basin, China, were studied by FT-IR and the oxygen-containing groups found in these coals are aromatic hydrocarbons, aliphatic carbons, aromatic carbons, and carboxyl (Yao 2011).

The oxygen content of sub-bituminous coal was also discussed by Ruberto et al (1977) in his solvation studies, where it was concluded that a significant portion of the oxygen occurs in saturated ether functional groups α or β to the aromatic moieties or as furan systems. Hayatsu et al. (1978a, b) found significant quantities of phthalan and xanthone in lignite; xanthone and dibenzofuran in bituminous coal, and dibenzofuran in anthracite coals (Davidson 1982). Phenolic acids were also isolated from coal, which show a relationship between lignins and coals. From the available works in the literature, it can be also stated that the oxygen content of coal generally decreases with rank.

1.6.2.2 Nitrogen

The nitrogen functionality in coal is the representative of plant and animal proteins, nitrogen-rich bacteria, and plant alkaloids. Nitrogen concentrations have been reported to be in the range of 0.5%–2.0% (Meyers 2012). It has also been reported that coals commonly contain 1%–2% nitrogen, bituminous coals typically contain 1.5%–1.75% nitrogen, and anthracites generally contain <1% nitrogen. Most of the nitrogen in coal-tar

TABLE 1.4

General Assignments of Some Important FT-IR Stretching Frequencies for Functional Groups in Few Northeast Indian Coals

Stretching Frequencies cm^{-1}					Assignments
Coal Sample-1	Coal Sample-2	Coal Sample-3	Coal Sample-4	Coal Sample-5	
3752	3996		3698	3697	O–H str.
	3651		3655	3653	O–H str.
	3620		3621	3621	O–H str.
3412	3396	3411	3400	3389	O–H str. NH str.
3240	3280	3240	3200	3242	O–H str., NH str.
3020	3160	3020	2953	2926	CH_3 str., CH_2 str., al. CH str.
2953	3120	2919	2921	2920	CH_3 str., CH_2 str., al. CH str.
2920	2920	2850	2848	2851	CH_3 str., CH_2 str., al. CH str.
2849	2851				CH_3 str., CH_2 str., al. CH str.
1610	1607	1682	1610	1607	ar. $\text{C}=\text{C}$ str., $\text{C}=\text{O}$ str.
1558		1611			ar. $\text{C}=\text{C}$ str., $\text{C}=\text{O}$ str.
1436	1438	1433	1432	1436	CH_3 assym. def., CH_2 scissor. ar $\text{C}=\text{C}$ str.
1372	1400	1376	1401	1400	Aliph CH_3 , CH_2 str.
1320	1376	1300	1375	1165	CH_3 symm. def.
1163	1300	1202	1165	1090	CH_3 , def., $\text{C}-\text{O}$ str.
1091	1167	1165	1092	1031	$\text{C}-\text{O}$ str., Car–O–Car str.
1031	1090	1093	1032	1008	$\text{C}-\text{O}$ str., Car–O–Car str., Q
1008	1051	1032	1008	938	$\text{C}-\text{O}$ str. (alcohol), $\text{C}-\text{O}-\text{C}$ str., Cal–O–Cal str.
910	1008	1007	939	913	Car–O–Car str.
960	939	866	913	798	Aromatic band
800	913	810	798	778	Aromatic rings
780	798	748	779	752	Substituted benzene rings with 2 neighbors H
744	779	695	750		Hydrogen atoms in meso-position (anthracene) angular condensed ring system/ α -substituted benzene rings, monosubstituted benzene rings, H, Q
692	754	628	695		Condensed ring system
627	629	599	535		H-atom in condensed ring system
533	537	513	470		H-atom in condensed ring system
471	471	472			Quartz
420	431		430		Pyrite

and in liquefaction products is found as pyridines, condensed pyridines, pyrroles, nitriles, quinolines, indoles, and carbazoles. Thus, it is generally believed that most of the nitrogen in coal is incorporated in heterocyclic rings with small amounts of nitrogen-containing side chains (Davidson 1982).

1.6.2.3 Sulfur

Sulfur is of most important concern due to its environmental impacts during coal utilization. Hence, there is a considerable amount of works relating to the sulfur chemistry in coal (Baruah et al. 2006; Saikia et al. 2014a, b, c, d). Sulfur has a similar chemistry to oxygen, but less is known about organic sulfur in coal compared with organic oxygen. Heterocyclic sulfur compounds have been identified in coals but very few studies have concentrated on the organic sulfur functional groups in coal. However, Attar and Dupuis (1979) have reported data on these functionalities in different coals. Table 1.5 shows the distribution of organic sulfur groups in five coals, which shows that the content of thiols ($-\text{SH}$) is substantially larger in

lignites and high-volatile bituminous coals than in low-volatile bituminous coals. The fraction of aliphatic sulfides ($\text{R}-\text{S}-\text{R}$) remains approximately constant at 18%–25%. The data indicate that larger fractions of the organic sulfur are present as thiophenic sulfur in higher ranked coals than in lower ranked ones. The data on $-\text{SH}$, $\text{R}-\text{S}-\text{R}$, and thiophenic sulfur are explained by suggesting that the coalification process causes the organic to change from $-\text{SH}$ through $\text{R}-\text{S}-\text{R}$ to thiophenes in condensation reactions (Speight 2013).

1.6.2.3.1 High-Sulfur Coals

High-sulfur coals are found throughout the world with exception to Australia, where most of the coals are low in sulfur content (Stephen 1986). However, the sulfur content of coals is seen to be quite variable. The low sulfur content in coal becomes an important consideration during coal utilization in thermal plants. It is present in coal in forms such as pyritic sulfur, sulfate, and organic sulfur. Organic sulfur is chemically bonded to the carbon atoms in the coal structure.

TABLE 1.5
Distribution of Organic Sulfur Groups in Five Coals

Coal	Organic S (wt%)	Organic S Accounted (%)	Thiolic	Thiophenolic	Aliphatic Sulfide	Aryl Sulfide	Thiophenes
Illinois	3.2	44	7	15	18	2	58
Kentucky	1.43	46.5	18	6	17	4	55
Martinka	0.60	81	10	25	25	8.5	21.5
Westland	1.48	97.5	30	30	25.5	—	14.5
Texas lignite	0.80	99.7	6.5	21	17	24	31.5

Source: Attar, A. and Dupuis, F., *Am. Chem. Soc.*, 24(1), 166, 1979.

TABLE 1.6
Distribution of Sulfur Functional Groups in Assam Coal (wt%)

Coal	Mercaptan	Disulfide/Thiol	Thio-Ether	Thiophene	Pyrite	Sulfate	Thioketone
Ledo (India)	0.30	1.70	0.50	0.90	0.76	0.35	1.59

Pyritic sulfur occurs in coal as grains of the mineral pyrite (FeS_2). The amount of pyritic sulfur in coal is highly variable, depending on the geologic conditions. Sulfate occurs generally as iron or calcium sulfates. Moreover, the occurrence of another type of sulfur, termed as *secondary sulfur*, containing Fe-S moieties associated with coal organic matter in high-sulfur Assam coals was reported elsewhere (Baruah 1984, 1992). The sulfur phases are reported to be rich in ^{34}S isotopes for coals in the Pannonian basin, indicating the marine bacterial sulfate reduction during their formation (Hármor-Vidó and Hármor 2007). The vitrinites in coals show extreme anomalies in reflectance due to the high proportions of organic sulfur (Ward et al. 2007). Turner and Richardson (2004) examined the geological factors influencing the regional, stratigraphic, and between- and within-seam variations in sulfur content of coals in the Westphalian A and B Coal Measures in the Northumberland Coalfield of Northeast England. The relationships between sulfur abundance in coal seams and depositional environments of coals from the United States, China, the United Kingdom, Germany, Hungary, Turkey, Indonesia, and Brazil were reviewed and it was concluded that the variation of sulfur in coals is closely related to the depositional environments of coal seams (Chou 2012). The coals from northeastern region of India have high sulfur contents (Baruah et al. 2006). They generally contain 2%–8% sulfur, where 75%–90% is organically bound, while the rest is in inorganic form, namely sulfate and pyritic sulfur. The high organic sulfur coals are also found in the Upper Permian marine carbonate successions (Heshan Formation) in the Heshan Coalfield, central Guangxi, southern China (Longyi et al. 2003). These Late Permian low-volatile bituminous coals of Heshan Coalfield of southern China are termed as *super high-organic sulfur* (5.13%–10.82%) (Dai et al. 2013). The organic sulfur present in these coals is generally aliphatic or aromatic thiols,

aliphatic or mixed sulfides, aliphatic or aromatic disulfides, heterocyclic compounds of the thiophenic types, and so on. Kumar and Srivastava (2013) have concluded that the sulfur present in Assam coal (India) is in the forms of mercaptan, disulfide/thiol, thioether, thiophene, pyrite, sulfate, and thio-ketone (Table 1.6).

1.7 CHEMICAL STRUCTURE OF COAL

The concept of coal structure is difficult to define, as the macromolecules of coal are not composed of repeating mono-organic units (Gorbaty and Larsen 1982). The structures had been built on the basis that they were characterized by values of the above parameters (such as elemental composition, carbon and hydrogen aromaticities, number of rings, and size of aromatic cluster), as well as the total organic matter of the coal or its major petrographic components. Thus, the macromolecular character of coal (quasi-polymeric chains and/or polymeric sheets depending on the particular type of coal) and their nonpolymeric component of small organic molecules are embedded in a polymeric matrix. Coal from different geological time periods and different geographic areas may differ in composition and physico-chemical properties. The structural information, which had been thought to be generally valid for coal, obtained after different investigations may, in fact, only be so for coals of a particular region or geological age. The macromolecular skeletal structural models for coal were well described in the literature (Gorbaty and Larsen 1982). Two such model structures of bituminous coal are shown in Figures 1.4 and 1.5. The investigation of the chemical structures of coal has led to comprehensive and well-defined results on the basis of development of spectroscopic methods. These are FT-IR, ultraviolet-visible spectroscopy, X-ray structural analysis, solid-state nuclear magnetic resonance (NMR), and so on. X-ray diffraction studies provide useful information about the internal arrangement of atoms in

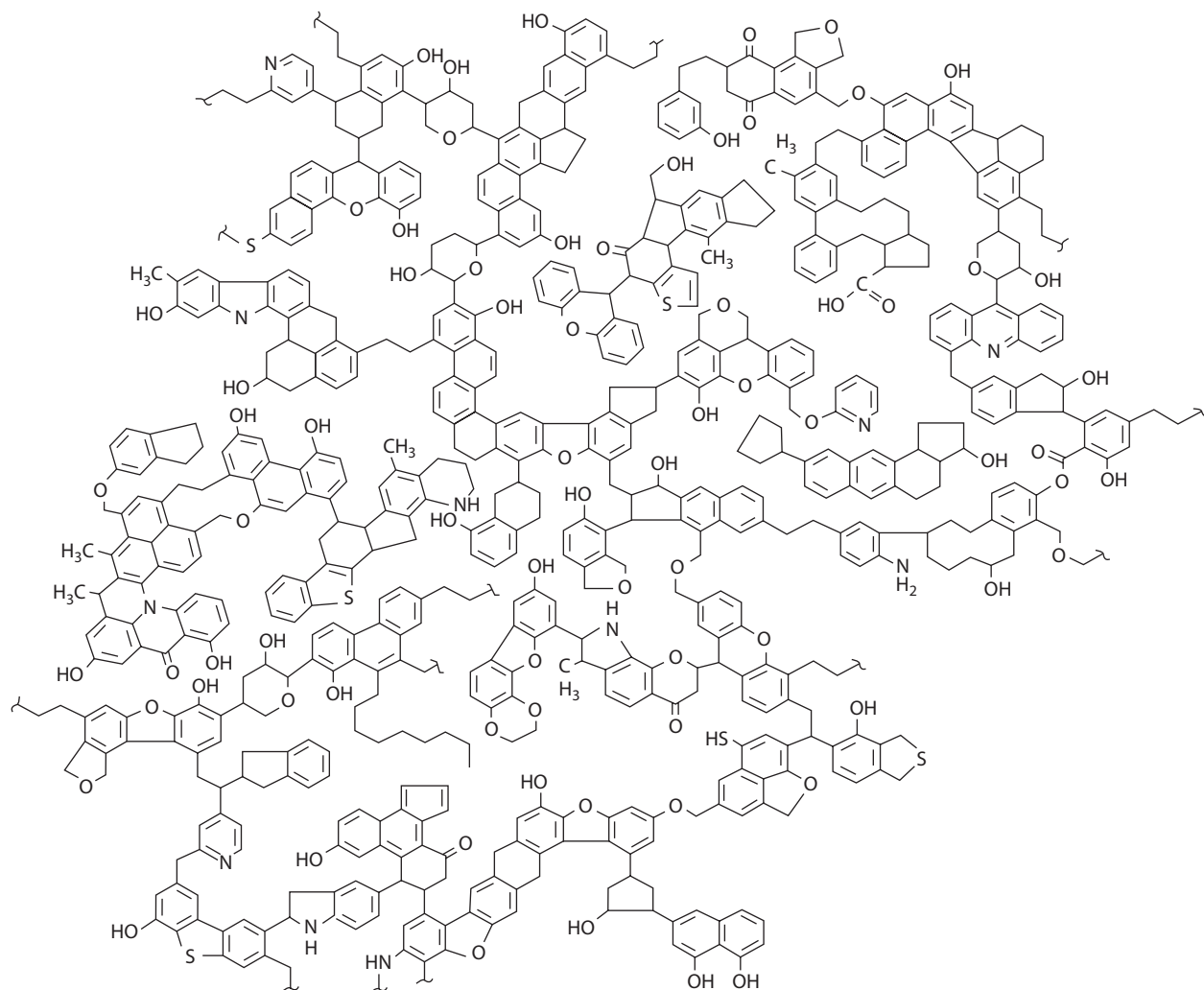


FIGURE 1.4 Model of coal structure provided by Wiser. (From Wiser, W.H., Conversion of bituminous coal 'to liquids and gases: Chemistry and representative processes, *Magnetic Resonance: Introduction, Advanced Topics and Applications to Fossil Energy*. L. Petrakis, and J.P. Fraissard (Eds.), Reidel, Dordrecht, The Netherlands, 325, 1984.)

coal (Saikia et al. 2007a, b, 2009a, b, c). This arrangement in coal is a vital factor, which affects many physical properties in relation with coal utilization.

Modern conceptions of the chemical structure of coals is well described by various researchers in numerous publications (Alvarez et al. 2012a, b, 2013; Barsky et al. 2009; Castro-Marcano and Mathews 2011; Castro-Marcano et al. 2012; Duane et al. 1982; Margriet et al. 1992; Mathews and Chaffee, 2012; Mathews and Sharma 2012; Mathews et al. 2011, 2014; Tselev et al. 2014). Summarizing the experimental results of coal structure allows considering the *molecule* of this substance as a set of various individual structures, mainly of aromatic and aliphatic nature. They are connected with each other by the forces of different nature, value, and kind of the bond (covalent, donor-acceptor or hydrogen bonds, polyconjugations owing to electrons delocalization, van der Waals forces, etc.). It is also reported that the organic coal substance is a totality of packs of condensed aromatic nuclei with side nonaromatic groups, including oxygen, nitrogen, sulfur, and other hetero-atoms,

which chemically bond the adjoined packs into three-dimensional polymer (Barsky et al. 2009). Such approach suggests that during coalification, the carbon-oxygen bonds are changed for the carbon-carbon ones in the side radicals.

1.7.1 RANDOM LAYERS (TURBOSTRATIC STRUCTURE) IN CHEMICAL STRUCTURE OF COAL

X-ray diffraction technique has been widely applied for the structure characterization of carbon materials and has given useful information. It may be applied for evaluating the carbon-stacking structure of coals. Different X-ray structural parameters can be determined from different parts of the scattering curve. The large variety of organic and inorganic materials involved in the formation of coal makes them highly heterogeneous, both in physical and chemical structures. One aspect of heterogeneity in coals is thus related to their physical structure, which is composed of a macromolecular cross-linked network and a molecular compound. X-ray diffraction

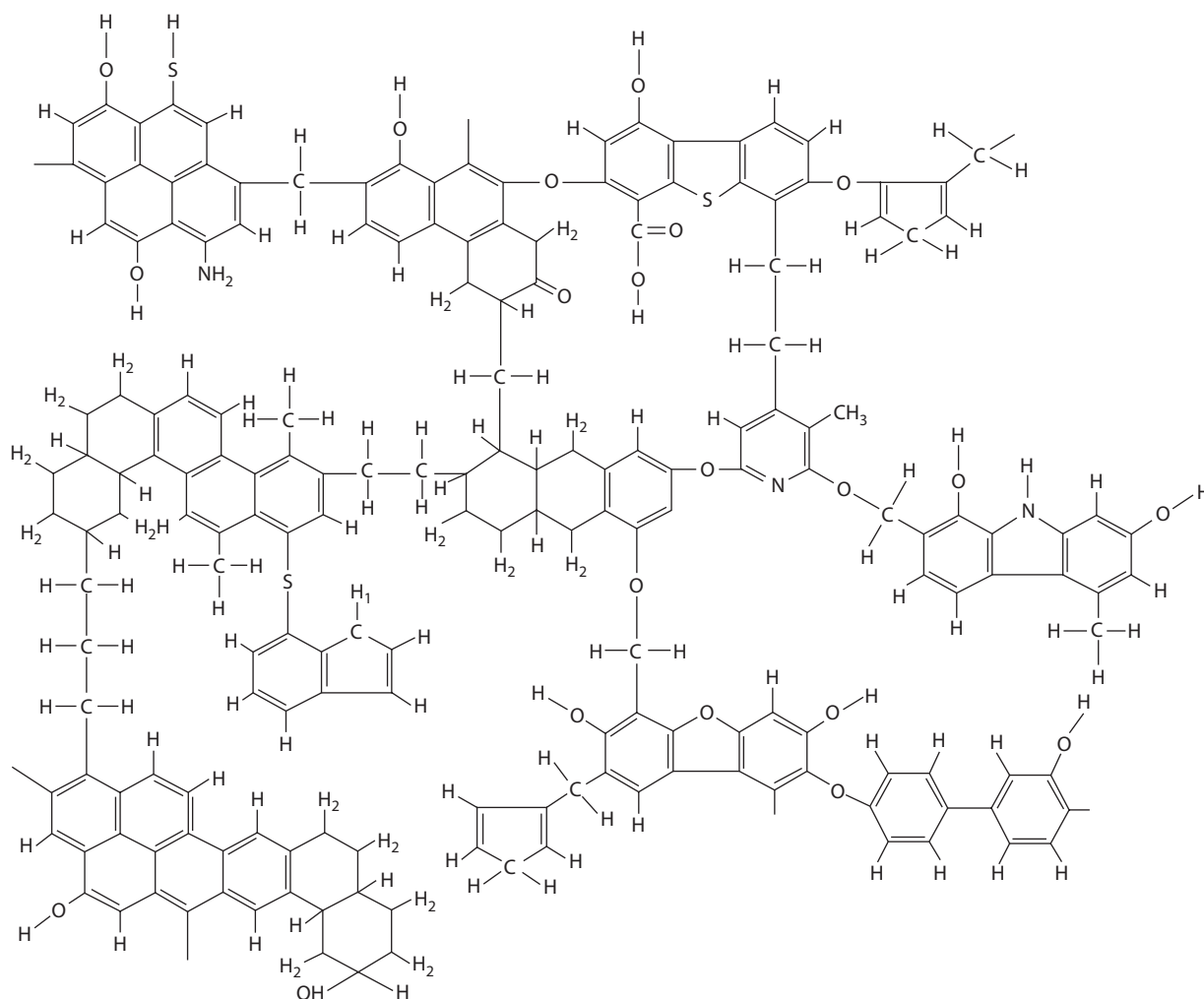


FIGURE 1.5 Model of coal structure provided by Shinn. (From Shinn, J.H., *Fuel*, 63, 1187, 1984.)

has been one of the few orthodox methods that have been used to estimate the size of the aromatic lamellae in coal, the average distance between lamellae and the mean bond distance. According to the visual inspection of the reduced intensity profile of the Assam (India) coal, the observation that can be made is that it contains a short-range graphite-like structure, that is, crystalline carbon, which is extremely small, giving rise to three diffuse peaks (Boruah et al. 2008). These crystalline carbons have an intermediate structure between graphitic and amorphous state, so-called turbostratic structure or random layer lattice structure (Biscoe and Warren 1942). This means that coal contains stacked aromatic layers, which are strongly parallel and equidistant, but each having a completely random orientation in plane and about the layer normal. It is reported to understand the short-range structural features, to determine the relationship(s) between the aryl/alkyl carbon ratio, and the size of the average polycyclic aromatic unit in coal from Makum coalfield, Assam, India. An X-ray scattering analysis of the average polycyclic aromatic unit in coal indicates that the aromatic fraction in this coal is 74%, with the aliphatic fraction correspondingly estimated to be 26% (Boruah et al. 2008) (Table 1.7).

1.8 ROCK TYPES AND MINERAL MATTERS IN COAL

1.8.1 ROCK TYPES

Physically distinguishable bands that are observed in lignite (brown soft coal) or coal (hard coal) are known as *rock types* or *lithotypes*. According to the International Committee for Coal Petrology (ICCP) (1993), the lithotype group of soft brown coal is further divided as lithotype based on structure as given in Table 1.8. These groups are designated based on the occurrence of components such as xylite (coalified woody material), groundmass (fine detrital humic material), and mineral matter. Thus, the lithotype groups recognized by ICCP classification are as follows (see also Table 1.8):

1. *Matrix coal* consists of a fine detrital humic ground-mass and is homogeneous in appearance with yellow to dark brown in color. Plant fragments may also be embedded in the groundmass and these coals show some stratification. Matrix coals are common in Paleogene–Neogene soft brown coals (Thomas 2013).

TABLE 1.7
X-Ray Structural Parameters of an Assam Coal

Coal	D-Value for (002) Plane, Å	L ₀₀₂ (Lc) Å	No of Layers	No of Atoms Per Layer	L ₁₀ (La) Å	γ-Band Å
Ledo	3.42	7.58	2	8	4.86	4.42

Source: Boruah, R.K. et al., *J. Appl. Crystallogr.*, 41, 27–30, 2008.

TABLE 1.8
Lithotype Classification for Soft Brown Coals

Lithotype Group (Constituent Elements)	Lithotype (Structure)	Lithotype Variety (Color; Gelification)
Matrix coal	Stratified coal	Brown (weakly gelified) coal Black (gelified) coal
	Unstratified coal	Yellow (ungelified) coal Brown (weakly gelified) coal Black (gelified) coal
Xylite-rich coal		
Charcoal-rich coal		
Mineral-rich coal		

Sources: Taylor, G.H. et al., *Organic Petrology*, Gebruder Borntraeger, Berlin, Germany, 704, 1998; ICCP, *International Handbook of Coal Petrography*, 3rd Supplement to 2nd Edition. University of Newcastle up on Tyne, London, 1993.

2. *Xylite-rich coal* includes coals with more than 10% of xylite (woody fibrous tissue). The groundmass is detrital and may or may not be stratified. It is the dominant lithotype and found in all brown coals. Its characteristics are thought to be the decomposition of trees and shrubs in the peat-forming mire.
3. *Charcoal-rich coal* contains more than 10% charcoal. The coal can be weakly or strongly stratified, occurring as lenses and occasionally with more persistent layers. The coal is brownish-black and has a coke-like appearance. It is considered to be the product of burned forest swamps. If such coal is stratified, it is indicative of water or wind transported residues in an open-swamp environment.
4. *Mineral-rich coal* includes all kinds of mineralization of the different brown coal lithotype groups and should be visible to the naked eye. The inorganic materials present typically include quartz, clay, carbonates, sulfides, and other minerals (Thomas 2013). The hard coals may be classified into two coal types at macroscopic scale as the humic or banded coals and the sapropelic or nonbanded coals, whose descriptions have already been discussed in Section 1.3.

1.8.2 MINERAL MATTERS IN COAL

Mineral matters of coal are the important structural components being studied recently. The determination of major and trace elements in coals is of primary importance and represents a significant challenge for assessments and management of their

environmental issues of coal processing. Mineral matter refers to all forms of inorganic materials present in coal and therefore, includes various metals and anions as well as mineral phases. It also refers to the elements that are bonded in various ways to the organic (C, H, O, N, and S) components in coal. The distribution and concentrations of different metals and mineral matter content in coal significantly vary for different coalfields. The term *mineral* refers only to the discrete mineral phases. Minerals in coal occur as discrete grains or flakes in one of five physical modes: (1) disseminated, as tiny inclusions within macerals; (2) layers or partings (also lenses), where fine-grained minerals predominate; (3) nodules, including lenticular or spherical concretions; (4) fissures (cleat and fracture fillings and also small void fillings); (5) rock fragments megascopic masses of rock replacements of coal as a result of faulting, slumping, or related structures (Harvey and Ruch 1986). The most common minerals and mineral groups in coal seams are quartz, clays, feldspars, sulfides, and carbonates. Of the clay minerals, kaolinite is quite common (Gluskoter 1967; Rao and Gluskoter 1973), as is illite–smectite. Siderite, calcite, and dolomite are commonly observed carbonate minerals in coal. Pyrite is the most commonly found sulfide mineral in coal (Gluskoter et al. 1977). Clays (primarily illite and kaolinite) and quartz are common clastic minerals in coal, and in some cases, can account for nearly all of the mineral matter present (Stach et al. 1982). Syngenetic quartz is also present in coal seams. Quartz dissolution has been reported from mire-type environments under reducing conditions (Bennett et al. 1988). Syngenetic quartz and clay may appear as cell and pore infillings (Ward 2002), or as coatings or overgrowths on clastic mineral grains.

The majority of iron present in coal mineral matter is in the form of syngenetic and epigenetic iron disulfides. The most common sulfide mineral in coal is found to be pyrite. The pyrite in coal generally has syngenetic or early epigenetic origins. However, organically bound sulfur is also common in coals. Iron is also present in the form of siderite, which is usually present in coal as small (1–2 mm) nodules, often associated with vitrinite and clay layers (Stach et al. 1982). Siderite is thought to form syngenetically or during early diagenesis. The sulfides make up a significant portion of the epigenetic mineral fraction in coal. Pyrite is also found associated with other sulfides or oxides, in quartz veins in coals as well as in coal beds.

Carbonates are found as epigenetic minerals in the form of veins or cleat fillings in coal (Stach et al. 1982). Common epigenetic carbonates include calcite, ankerite, siderite, and dolomite. The authigenic calcium is thought to be derived from groundwater (Cecil et al. 1978). Thus, there is more possibility of calcium carbonate minerals to be found in coals

produced from topogenous mires than in coals produced by ombrogenous mires (Cecil et al. 1985; McCabe 1993).

Phosphate minerals may contain significant amounts of the rare earth elements present in coal (Willett et al. 2000). Apatite is typically the most common of the phosphate minerals occurring in coals. Other reported forms of phosphate minerals include aluminophosphates (Crowley et al. 1993; Finkelman and Stanton 1978; Rao and Walsh 1997, 1999; Ward et al. 1996). Phosphate minerals are present as cell and pore fillings, in concentrated layers within coal units, and aluminophosphates are known to be associated with tonsteins (Bohor and Triplehorn 1993; Hill 1988; Schatzel and Stewart 2012).

The mineral matters present in coal are generally determined through the X-ray diffraction investigation. Some of the principal minerals present in coal are given in Table 1.9. The coals in the United States are enriched with clay minerals, pyrite, quartz, calcite, marcasite, sphalerite, feldspar, hematite, siderite, ankerite, and so on (Harvey and Ruch 1986).

TABLE 1.9
Principal Minerals Found in Coal

	Silicates		Carbonates
Quartz	SiO ₂	Calcite	CaCO ₃
Chalcedony	SiO ₂	Argonite	CaCO ₃
Kaolinite		Dolomite	CaMg(CO ₃) ₂
Illite	Al ₂ Si ₂ O ₅ (OH) ₄	Ankerite	(Fe,Ca,Mg)CO ₃
Smectite	K _{1.5} Al ₄ (Si _{6.5} Al _{1.5})O ₂₀ (OH) ₄	Siderite	FeCO ₃
Chlorite	Na _{0.35} (Al _{1.67} Mg _{0.33})Si ₄ O ₁₀ (OH) ₂	Dawsonite	NaAlCO ₃ (OH) ₂
Interstratified clay mineral	(MgFeAl) ₆ (AlSi) ₄ O ₁₀ (OH) ₈	Strontianite	SrCO ₃
Feldspar	KAlSi ₃ O ₈	Witherite	BaCO ₃
Toumaline	NaAlSi ₃ O ₈	Alsonite	CaBa(CO ₃) ₂
Analcime	CaAl ₂ Si ₂ O ₈	Sulfates	
Clinoptilolite	Na(MgFeMn) ₃ Al ₆ B ₃ Si ₆ O ₂₇ (OH) ₄	Gypsum	CaSO ₄ ·2H ₂ O
Heulandite	NaAlSi ₂ O ₆ ·H ₂ O	Bassanite	CaSO ₄ ·1/2H ₂ O
	(NaK) ₆ (SiAl) ₃₆ O ₇₂ ·20H ₂ O	Anhydrite	CaSO ₄
	CaAl ₂ Si ₇ O ₁₈ ·6H ₂ O	Barite	BaSO ₄
Sulfides		Coquimbite	Fe ₂ (SO ₄) ₃ ·9H ₂ O
Pyrite	FeS ₂	Rozentite	FeSO ₄ ·4H ₂ O
Marcasite	FeS ₂	Szomolnokite	FeSO ₄ ·H ₂ O
Pyrrhotite	Fe _(1-x) S ₂	Natrojaarosite	NaFe ₃ (SO ₄) ₂ (OH) ₆
Sphalerite	ZnS	Thenardite	Na ₂ SO ₄
Galena	PbS	Glauberite	Na ₂ Ca(SO ₄) ₂
Stibnite	SbS	Hexahydrite	MgSO ₄ ·6H ₂ O
Milerite	NiS	Tschermigite	NH ₄ (SO ₄) ₂ ·12H ₂ O
Phosphates		Others	
Apatite	Ca ₅ F(PO ₄) ₃	Anatase	TiO ₂
Crandalite	CaAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O	Rutile	TiO ₂
Gorceixite	BaAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O	Boehmite	Al ₂ O ₃ ·OH
Goyazite	SrAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O	Geothite	Fe(OH) ₃
Monazite	(Ce,La,Th,Nd)PO ₄	Crocoite	PbCrO ₄
Xenotime	(Y,Er)PO ₄	Chromite	(Fe,Mg)Cr ₂ O ₄
		Clausthalite	PbSe
		Zircon	ZrSiO ₄

Source: Ward, C.R., *Int. J. Coal Geol.*, 50, 135–168, 2002.

It has been reported that in northeast Indian high-sulfur coals, the major minerals (>5%) are identified in the crystalline matter of coal, which include quartz, kaolin, illite, feldspar, calcite, pyrite, and gypsum (Baruah 2008, 2009). The other minerals commonly present in minor (1%–5%) and accessory (<1%) amounts in coal.

1.9 COAL SAMPLING (IN SITU AND EX SITU) AND COAL ANALYSIS

1.9.1 COAL SAMPLING

Samples are the representative fractions of a body of material that are required for testing and analysis in order to assess the nature and composition of the parent body. They are collected by approved methods (e.g., ASTM and BIS) to protect them from contamination and chemical changes. The variability of coal makes coal sampling a difficult task. Sampling of coal is required to determine the suitability of coal for further investigation, for mine development program and for the quality study of the coal mined in opencast and underground mines. Sampling is done in two methods: in situ and ex situ sampling.

In situ coal samples are taken from surface exposures, exposed coal seams in opencast, underground workings, and from drill cores and cuttings. Ex situ samples are taken from run of mine coal streams, coal transport containers, and coal stockpiles. Sampling may have to be undertaken in widely differing conditions, particularly those of climate and topography. It is important to avoid weathered coal sections, coals contaminated by extraneous clay or other such materials, coals containing a bias of mineralization, and coals in close contact with major faults and igneous intrusions (Thomas 2013).

1.9.1.1 In Situ Sampling

One of the best sampling methods for in-seam coals is the channel sampling method. In this method, the coal is normally sampled perpendicular to the bedding. A channel of uniform cross section is cut manually into the coal seam, and all the coal within the cut section is collected on a plastic sheet placed at the base of the channel. Most channels are around 1.0 m across and samples should not be less than 15 kg m⁻¹ of coal thickness (Thomas 2013). The sampling of the full seam actually provides overall quality of the seam including the mineral matters within the coal (Speight 2013).

In the pillar sampling method, a large block of undisturbed coal is usually sampled from some specific areas of potential or known problems in underground coal mining, where the sampling scheme is similar to that of the channel sampling. Core sampling is an integral part of coal exploration and mine development, which has the advantage of producing nonweathered coal including the coal seam floor and roof, and unlike channel samples, core samples preserve the lithological sequence within the coal seam. The coal samples, cylindrical in nature, preserve the lithological sequence within the coal seam. However, the cleaning of the core samples has to be done if drilling fluids have been used, and then

also lithologically logged to study the coal thickness and to adjust the core recovery (Speight 2013; Thomas 2013). Bulk sampling may also be collected from a site already channel sampled, loaded into drums, numbered and shipped to the selected test center. This type of sampling checks the swelling properties of coal and is used to rank coal as high-pressure coal and low-pressure coal (Speight 2013; Thomas 2013).

1.9.1.2 Ex Situ Sampling

Ex-situ coal sampling is carried out on moving streams of coal, from rail wagons, trucks, barges, grabs, or conveyors unloading ships, from the holds of ships and from coal stockpiles. The various practices used in collecting ex situ samples and the mathematical analysis for representative of the samples, that is, quality control, is reported by Laurila and Corriveau (1995). Increments of samples are taken by using four methods:

1. Systematic sampling, where increments are spaced evenly in time or in position over the unit.
2. Random sampling, where increments are spaced at random but prerequisite numbers are taken.
3. Stratified random sampling, where the unit is divided by time or quantity into a number of equal strata and one or more increments are taken at random from each (Thomas 2013).
4. Coning and quartering, which involve pouring the sample so that it takes on a conical shape, and then flattening it out into a cake. The cake is then divided into quarters; the two quarters that sit opposite one another are discarded, while the other two are combined and constitute the reduced sample. The same process is continued until an appropriate sample size remains.

1.9.2 COAL ANALYSIS

The analysis of coal involves specific analytical methods to measure the particular physical and chemical properties of coals. These methods are used primarily to determine the suitability of coal for coking, power generation, or for iron ore smelting in the manufacture of steel. The coal analyses are done in three categories: proximate analysis, ultimate analysis, and miscellaneous analysis. Proximate analysis is the determination, by prescribed methods, of the contents of moisture, volatile matter, ash, and fixed carbon (by difference) content. On the other hand, the ultimate analysis of coal and coke involves the determination of carbon, hydrogen, total sulfur, nitrogen, and ash content of the coal, and the estimation of oxygen content by difference. Miscellaneous analysis is a collective category for various types of physical and chemical tests for coal that are commonly requested by coal producers and buyers. This category includes tests such as the determination of calorific value, analysis of the forms of sulfur, carbon, chlorine analysis, major and minor elements in ash analysis, trace element analysis, carbon dioxide analysis, determinations of free-swelling index, grindability, plastic properties of coal, and ash fusibility.

1.9.2.1 Proximate Analysis

The standard test method for proximate analysis (ASTM D-3172) covers the methods of analysis associated with the proximate analysis of coal and coke.

1. **Moisture:** Moisture in coal may occur in four possible forms. It can be surface, hygroscopic, decomposition, and mineral moisture. The surface moisture results from water held on the surface of coal particles or macerals. Hygroscopic moisture is caused by water held by capillary action within the microfractures of coal. Decomposition moisture is due to water held within the coal's decomposed organic compounds. Mineral moisture is a result of water, which comprises part of the crystal structure of hydrous silicates, especially clay minerals. Thus, the moisture is usually determined as total moisture, calculated as the loss of weight between the untreated (1 g coal) and analyzed samples. Moisture can be determined by different methods, including heating coal with toluene, drying in a minimum free-space oven at 150°C in nitrogen atmosphere, and drying in air at 100°C to 105°C. The first two methods can be used for low-rank coals. The third method is for high-rank coals (for low-rank coals, oxidation may take place). The third method can also be used for determination of the inherent moisture. However, the analysis should be run in vacuum.
2. **Volatile matter:** Volatile matter of coal is determined by using standard test methods, that is, ASTM D-3175; ISO 562, which is related to the percentage of volatile products excluding the moisture vapor released during the heating of coal or coke under rigidly controlled conditions (Speight 2013).
3. **Ash content:** The residue remained after the combustion of coal under standard conditions (ASTM D-3174; ISO 1171) is called as *ash content*, which is composed primarily of oxides and sulfates. The ash is formed due to the chemical changes taking

place in the mineral matter during the ashing process. The quantity of ash can be more than, equal to, or less than the quantity of mineral matter in coal, depending on the nature of the mineral matter and the chemical changes that take place during the ashing process.

4. **Fixed Carbon:** Fixed carbon is the difference of these three values summed and subtracted from 100. In low-volatile materials, such as coke and anthracite coal, the fixed-carbon value equates approximately to the elemental carbon content of the sample.

The ranges of proximate and ultimate analyses of various ranks of coals are as shown in the Table 1.10.

1.9.2.2 Ultimate Analysis

It is already stated that the ultimate analysis of coal involves determination of the carbon and hydrogen, as well as sulfur, nitrogen, and oxygen (usually estimated by difference). Trace elements that occur in coal are often included as a part of the ultimate analysis. Thus, the standard method for the ultimate analysis of coal and coke (ASTM D-3176-89) includes the determination of elemental carbon, hydrogen, sulfur, and nitrogen, together with the ash in the material as a whole. Oxygen is usually calculated by difference. The test methods recommended for elemental analysis also include the determination of carbon and hydrogen (ASTM D-3178), nitrogen (ASTM D-3179), and sulfur (ASTM D-3177-02; ISO 334; ISO 351), with associated determination of moisture (ASTM D-3173) and ash (ASTM D-3174) to convert the data to a moisture-ash-free basis.

The carbon determination also includes carbon present as organic carbon in the coal substance and any carbon present as mineral carbonate. The hydrogen determination includes hydrogen present in the organic materials as well as hydrogen in all of the water associated with the coal. In the absence of evidence to the contrary, all of the nitrogen is assumed to occur within the organic matrix of coal. Oxygen occurs in both the organic and inorganic portions of coal. In the organic portion, oxygen is present in phenol groups,

TABLE 1.10
Composition and Property Ranges for Various Ranks of Coal (wt%)

	Anthracite	Bituminous	Sub-Bituminous	Lignite
Moisture (%)	3–6	2–15	10–25	25–45
Volatile matter (%)	2–12	15–45	28–45	24–32
Ash (%)	4–15	4–15	3–10	3–15
Fixed Carbon (%)	75–85	50–70	30–57	25–30
Carbon (%)	75–85	65–80	55–70	35–45
Hydrogen (%)	1.5–3.5	4.5–6	5.5–6.5	6–7.5
Nitrogen (%)	0.5–1	0.5–2.5	0.8–1.5	0.6–1.0
Oxygen (%)	5.5–9	4.5–10	15–30	38–48
Sulfur (%)	0.5–2.5	0.5–6	0.3–1.5	0.3–2.5

Source: Speight, J.G., *The Chemistry and Technology of Coal*, 3rd Edition, CRC Press, Taylor & Francis Group, Boca Raton, FL, 2013.

carboxyl, methoxyl, and carbonyl. The inorganic materials in coal that contain oxygen are the various forms of moisture, silicates, carbonates, oxides, and sulfates.

On the other hand, sulfur occurs in three forms in coal: (1) organic sulfur; (2) inorganic sulfur, that is, iron sulfides, pyrite, and marcasite (FeS); and (3) sulfate sulfur (e.g., Na_2SO_4 and CaSO_4). The elemental sulfur has also been reported to be present in coal (Baruah 1994). The reaction of elemental sulfur with coal aromatics account for the formation of organo-sulfur compounds in coals (Narayan et al. 1989).

The determination of chlorine content in coal is also important for its further utilization. It occurs predominantly as sodium, potassium, and calcium chlorides, with magnesium and iron chlorides present in some coals. There are two standard methods of determining chlorine in coal (ASTM D-2361 and ASTM D-4208). Method of determination of chlorine in coal generally includes combusting the coal sample with or without Eschka mixture, in an oxygen bomb and heating the mixture in an oxidizing atmosphere. Eschka mixture is a combination of two parts by weight of magnesium oxide and one part of anhydrous sodium carbonate.

The presence of mercury in coal is identified as a very dangerous environmental contaminant and its emission is an environmental concern. The test for total mercury (ASTM D-3684-01; ISO 15237) involves combusting a weighed sample in an oxygen bomb with dilute nitric acid absorbing the mercury vapors. The ultimate analyses also include determination of carbon dioxide (ASTM D-1756-02; ASTM D-6316), arsenic, and selenium (ASTM D-4606) (Speight 2013).

1.9.2.3 Thermochemistry of Coal

The thermochemistry of coal is important in determining the applicability of coal to a variety of conversion processes such as combustion, carbonization, gasification, and liquefaction. The thermal properties of coal include energy of activation, calorific value, ash fusibility, caking index, and swelling index. Generally, thermogravimetric analysis (TGA) is used to study the thermal properties of coals.

The calorific value is an important parameter for assessment of coal quality, which signifies the heat produced by the combustion of a unit quantity of coal in a bomb calorimeter, with oxygen and under a specified set of conditions (standard methods: ASTM D-121; ASTM D-2015; ASTM D-3286; ISO 1928). The calorific value is usually expressed as the gross calorific value or the higher heating value and the net calorific value or lower calorific value. The energy content of the coal can also be expressed as the *useful* heating value, which is an expression derived from the ash and moisture contents for noncaking coals through the formula

$$\text{Useful heating value (kcal/kg)}$$

$$= 8900 - 138$$

$$\times [\text{ash content (wt\%)} + \text{moisture content (wt\%)}]$$

The differences between the gross calorific value and the net calorific value are given by

$$\text{Net calorific value (BTU/lb)} = \text{gross calorific value}$$

$$- [(1030 \times \% \text{ total hydrogen} \times 9)/100]$$

Calorific value of coal can also be determined by means of various formulas, the most popular of which are as follows:

1. Dulong formula:

$$\begin{aligned} \text{Calorific value} &= 144.4(\%C) + 610.2(\%H) - 65.9(\%O) \\ &\quad - 0.39(\%O)^2 \end{aligned}$$

2. Dulong–Berthelot formula:

$$\begin{aligned} \text{Calorific value} &= 81370 + 345 \\ &\quad \left\{ \frac{[\%H - (\%O + \%N - 1)]}{8} \right\} \\ &\quad + 22.2(\%S) \end{aligned}$$

where:

% C, % H, % N, % O, and % S are the respective carbon, hydrogen, nitrogen, oxygen, and organic sulfur contents of the coal (all of which are calculated to a dry, ash-free basis). In both the cases, the values calculated are in close agreement with the experimental calorific values (Speight 2013)

The fusion characteristics of the coal ash either in a reducing or in an oxidizing atmosphere is provided by the ash fusibility test method (ASTM D-1857). Thus, it gives an approximation of the temperatures at which the ash remaining after the combustion of coal will sinter, melt, and flow. Sintering is the process by which the solid ash particles weld together without melting. The temperature points are measured by observation of the behavior of triangular pyramids (cones) produced from coal ash when heated at a specified rate in a controlled atmosphere (Speight 2013). The critical temperature points are as follows:

1. *Initial deformation temperature*: The temperature at which the first rounding or bending of the apex of the cone occurs. Cone is prepared from the coal ash.
2. *Softening temperature*: The temperature at which the cone has fused down to a spherical lump, in which the height is equal to the width of the base.
3. *Hemispherical temperature*: The temperature at which the cone has fused down to a hemispherical lump, at which point the height is one-half the width of the base.
4. *Fluid temperature*: The temperature at which the fused mass has spread out in a nearly flat layer.

The caking index of coal gives a measure of the caking properties, while swelling index indicates the degree of swelling that a sample of coal will undergo during carbonization. Both the parameters are important in the coal carbonization industries

(Speight 2013). In the caking index test, the maximum whole-number ratio of sand to coal in a 25 g mixture, on carbonization under standard conditions, produces a carbonized mass capable of supporting a 500 g weight and yielding less than 5% of loose, unbound material. The powdered coal, when heated in the absence of air coalesces into coherent mass. Then, this coherent mass swells and resolidifies into coke. The amount of swelling helps in the evaluation of the coking behavior of coal for industrial production of coke (Speight 2013).

1.10 ANALYTICAL METHODS FOR COAL ANALYSIS

The chemistry of coal has been receiving much attention among coal chemists because of their importance in chemical reactivity during various utilizations. However, detailed chemical characterization has been found to be extremely difficult and therefore, research on coal chemistry is still a challenging task and continues to be pursued intensively (Saikia 2009). There are comprehensive and well-defined results on the chemistry of coal on the basis of advance analytical methods. Thus, the coal can be analyzed through conventional and advanced bulk analytical techniques. The conventional techniques include proximate and ultimate analyses, ash fusion temperature, and petrographic analysis, which have already been discussed in Sections 1.9.2.1 through 1.9.2.3. The petrographic analysis can be done through various characterization techniques such as reflectance microscopy, NMR techniques, FT-IR spectroscopy, and X-ray techniques to study the organic matters in coal.

The advanced analytical techniques include differential thermal analysis (DTA), differential scanning calorimetry (DSC), thermomechanical analysis (TMA), chemical fractionation, X-ray fluorescence, X-ray diffraction, Mössbauer spectroscopy, TGA, Carbon-13 (^{13}C) and Proton (^1H) Nuclear Magnetic Resonance (NMR) spectroscopy, FT-IR spectroscopy, chromatographic techniques, and electron microscopy (scanning electron microscopy/transmission electron microscopy) (Gupta 2006). However, there are other advanced level multi analytical methods to the characterization of minerals associated with coals and to diagnose their potential risk (Silva et al. 2012).

TGA, DSC, and DTA techniques are useful tools for the study of combustion, pyrolysis behavior, and kinetics of coals. The TGA/DTA/DSC reveals the different types of reactions during coal combustion, formation of solid, liquid and gaseous products, and records the mass loss of the sample with time and temperature. Shi et al (2014), Gomez et al. (2014), and Huang et al. (1995) studied the different reactions during pyrolysis of coals and determined the coal rank through thermogravimetric analysis. DTA and DSC are employed to track the reaction type (e.g., endothermic or exothermic), calculate the kinetics and heat flow rates, and delineate Thermogravimetry (TG)/derivative thermogravimetry (DTG) combustion curves (Sis 2007). Different researchers have worked on pyrolysis, combustion characteristics of coals and coal blends, and the effect of coal particle size through study of TGA-DTG and DSC curves (Chang et al. 2009; Mustafa

et al. 1998; Sahu et al. 2010; Saikia et al. 2009a, b, c; Xiangguo et al. 2006).

Thermomechanical analysis is used to acquire knowledge on the fusibility, melting, and sintering behavior of coal particles, as well as information such as deposit strength and its influence on heat transfer. Both Bryant et al. (2000) and Gupta et al. (1999) had characterized the thermal properties of coal ash by using thermomechanical analysis.

The chemical fractionation of coal is also one of the techniques to determine the trace element's chemistry in coal. It provides species-specific information using three successive selective extractions of elements based on solubility that reflects their association in coal. There are three types of successive extractions: (a) by using water for removal of water-soluble salts containing elements such as sodium; (b) by using ammonium acetate to remove elements such as sodium, calcium, and magnesium that are ion exchangeable; and (c) by using hydrochloric acid or other to remove acid-soluble species such as alkaline earth sulfates and carbonates. The residual material typically consists of silicates, oxides, and sulfides.

The FT-IR spectroscopy is the most important tool for assessment of the functional groups present in coal structure and chars. It characterizes the inorganic and organic matter present in coal (Saikia et al. 2007a, b, c). FT-IR has been extensively used in the identification of the chemical structure of coals (Baruah and Khare 2010; Saikia et al. 2009a, c). Saikia et al. (2007a, b, c) used the difference FT-IR spectroscopy for evaluation of changes in coal structure during solvent extraction.

The X-ray fluorescence analysis is one of the most powerful techniques used for determination of trace elements, sulfur content, ash content, and yield of liquefied coal and also for analysis of effluents from coal conversion processes. Inductively coupled plasma and atomic absorption spectrometry are also used for determining the major and trace element contents of ash and coal and inductively coupled plasma can detect the hazardous trace elements such as As, Cd, and Pd in low parts per billion concentration range (Whateley 2002).

On the other hand, X-ray diffraction reveals the structural information of coal and chars and the changes in the crystalline structure of coal during conversion processes. X-ray diffraction can be used to identify the changes in the crystallite size for samples produced at different temperatures in a wide temperature range ($\sim 900^\circ\text{C}$ – 1500°C). Saikia et al. (2009b) reported the presence of graphene layers in Assam coal using X-ray diffraction technique. There are extensive studies on coal chemical structure by using X-ray diffraction methods (Saikia 2010; Saikia et al. 2009a, b, c; Van Krevelen 1993; Wertz 1998).

Electron probe microanalysis describes the chemical composition of the coal sample, while scanning electron microscopy describes the particle size, swelling of the particles during conversion, and the structure of coal/char/ash. The scanning electron microscopy and transmission electron microscopy identify the maceral composition, as well as the mineral matters in coal and explore the relationships between coal minerals and certain maceral types (Gluskoter and Lindahl 1973; Saikia et al. 2009c; Wall et al. 1998). Computer-controlled

scanning electron microscopy (CCSEM) is an advanced technique that provides information on mineral matters in coal including mineral types, their size distribution, and relationship between included and excluded minerals (Gupta et al. 1997; Saikia and Ninomiya 2011). It also provides a more robust analysis of coal mineral matters and their association, and it would be invaluable for resolving many complex questions in clean coal technology (Saikia and Ninomiya 2011).

Mössbauer spectroscopy provides information on the iron-bearing minerals in coal, which plays a significant importance in the study of slag formation in a coal combustion system. The speciation of iron and sulfur in coals has been extensively studied by Mössbauer spectroscopy and is well established (Waanders et al. 2003; Waanders and Bunt 2006). Due to the presence of iron in a large percentage of mineral matter appearing in coal, Mössbauer spectroscopy is a useful, and to a certain degree is a unique, analytical tool in the identification of iron-bearing minerals (Long and Stevens 1986; Montano 1981). Huggins and Huffman (1979) also studied the coal through the application of Mössbauer spectroscopy.

^1H NMR spectroscopy enables the functional groups present in coal to be identified and indicates the low and high molecular weight fractions of coals (Saikia et al. 2013). On the other hand, the solid-state ^{13}C NMR spectroscopy describes the average carbon skeletal structure of coal. The cross-polarization, magic angle spinning, and dipolar dephasing techniques permit direct measurement of the number and diversity of aromatic and aliphatic regions of the coal matrix (Hambly 1998). The ^{13}C NMR spectroscopy also determine the number of carbons per cluster, number of attachments per cluster, the number of bridges and loops, the ratio of bridge to total attachments, the average aromatic cluster molecular weight, and the average side chain molecular weight (Gupta 2006).

Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) is one of the latest developments in coal chemistry, which studies the molecular components or structural units of the polymeric organic solids. The combined use of solid-state NMR and Py-GC-MS provides information on the average structure and specific molecular components along with insights into the major and minor changes in coal structures during coal liquefaction processes (Song et al. 1991).

1.11 COAL PRODUCTS

Coal-based products play an increasingly important role in fulfilling the needs of energy, chemicals, and other gaseous products (Levine et al. 1982). The coal-based products can be classified as coal combustion products, coal-derived products, and other products.

1.11.1 COAL COMBUSTION PRODUCTS

Coal combustion products are produced primarily from the combustion of coal, which include fly ash, bottom ash, boiler slag, flue gas, fluidized bed combustion ash, cenospheres, and scrubber residues. The size, shape, and chemical composition of these material determine their beneficial reuse in different purposes;

for example, coal fly ash could be used as building materials. Moreover, these products when used beneficially can generate environmental, economic, and performance benefits (improved strength, durability, and workability of materials like concrete). However, coal fly ash also imposes health hazards to communities through exposure (Silva et al. 2012; Oliveira et al. 2014).

1.11.2 COAL-DERIVED PRODUCTS

Coal-derived products are associated with coal gasification, liquefaction, and carbonization. In coal gasification process, coal is typically exposed to steam and controlled amounts of air or oxygen under high temperatures and pressures. The coal structure breaks apart, initiating chemical reactions that typically produce a mixture of carbon monoxide, hydrogen, and other gaseous compounds. The syngas (H_2 v CO) produced can be used for power generation or manufacture of hydrogen, synthetic natural gas, or liquid fuel. The different coal-derived products from coal gasification are summarized in Figure 1.6.

Coal liquefaction is the process of conversion of coal into liquid fuels such as petroleum oil. The liquefaction processes are known as *direct* and *indirect liquefaction processes* (Figure 1.7). In direct liquefaction process, the pulverized coal is directly converted to liquid products by adding hydrogen in the presence of suitable catalysts at high pressure and temperature. Hydrogen is added to increase H/C ratio in the process. On the other hand, the Fischer–Tropsch process, known as *indirect liquefaction* of coal, is a process where the coal structure is completely broken down into synthesis gas (H_2 and CO) by gasification with steam and oxygen. The CO and H_2 molecules in the syngas are then combined catalytically to produce either hydrocarbon fuels such as synthetic gasoline or synthetic diesel, or oxygenated fuels (Williams and Larson 2003). The direct and indirect liquefaction processes along with their products are summarized in the Figure 1.7.

Carbonization of coal is a promising process to produce various commercial coal-based products. It is the destructive distillation of organic compounds in the absence of air and the production of carbon as coke, liquid such as fuel oil, and tar and gaseous products. This process is also used by steel industries to produce metallurgical coke for use in iron-making blast furnaces and other smelting processes. The gaseous by-product referred to as *coke oven gas* or *coal gas* is also formed along with ammonia, water, and sulfur compounds. Coke oven gas is a valuable heating fuel, which could also be used for generation of electricity. Other carbonization by-products are usually refined within the coke plant to produce commodity chemicals (Kaegi et al. 2000).

1.11.3 OTHER PRODUCTS

Coal tar produced from the carbonization of coal is a source of other valuable chemical products. The needle coke is produced from coal tar that also appears during coke production. It has excellent physical properties; it has low coefficient of thermal expansion and low electric resistance, along with less spalling and less breakage. Thus, several commercially

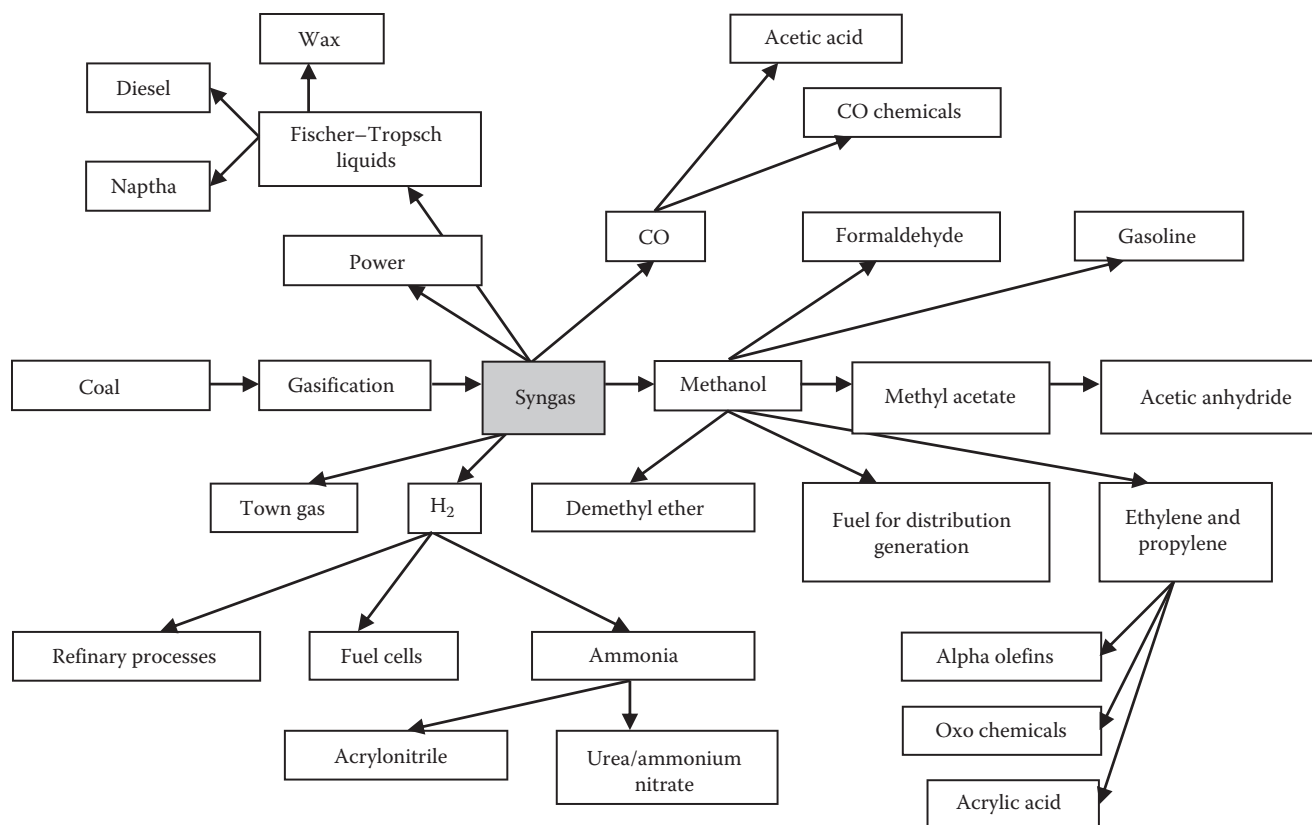


FIGURE 1.6 Summary of the products obtained from gasification process.

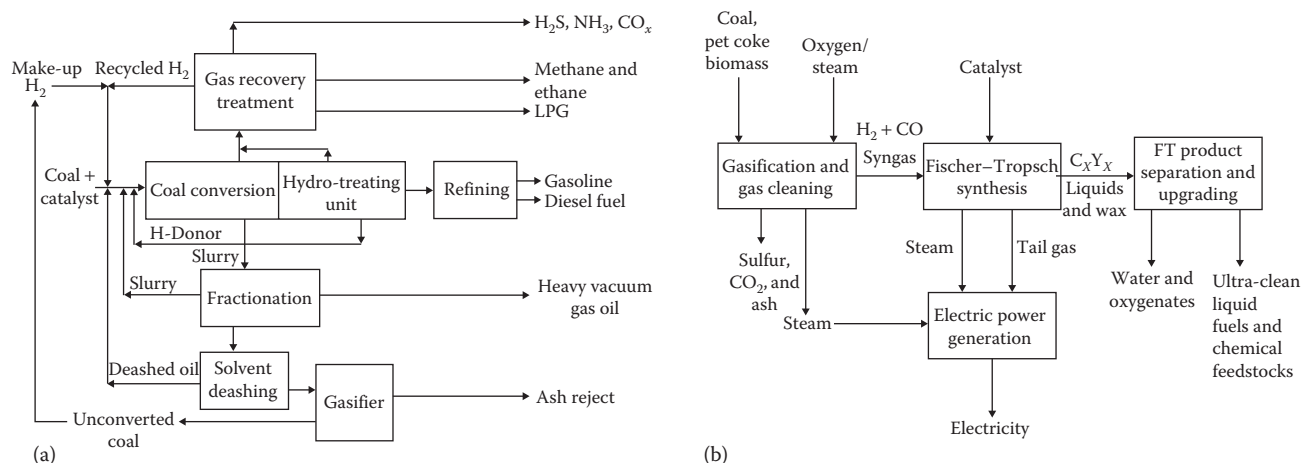


FIGURE 1.7 Products obtained through (a) direct and (b) indirect liquefaction of coals.

valuable chemical products can be produced from the by-products of coal. Refined coal tar is used in the manufacture of chemicals, such as creosote oil, naphthalene, phenol, and benzene. Ammonia gas recovered from coke ovens is used to manufacture ammonia salts, nitric acid, and agricultural fertilizers. Thousands of different products have coal or coal by-products as components: soap, aspirins, solvents, dyes, plastics, and fibers such as rayon and nylon. Coal is also an essential ingredient in the production of specialist

products such as activated carbon, carbon fiber, carbon foam, carbon nanotube, and fullerene. There is other value-added product such as humic acid, which could also be chemically produced. Das et al. (2013) reported the isolation of coal-based humic acid from the inferior coal and coal wastes from Mongchen coalfield, Nagaland (India). The humic acid has its utilization in industrial sectors particularly in the soil conditioning and complexation of heavy metals in environmentally polluted sites.

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2 Statistical Data on Worldwide Coal Reserves, Production, Consumption, and Future Demand

Mohan S. Rana and Faisal S. AlHumaidan

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Abstract: Coal is a solid fossil fuel that is primarily composed of carbon with variable quantities of other elements such as hydrogen, oxygen, sulfur, and nitrogen. Coal has formed over the course of many millions of years from dead organic material that was exposed to elevated temperature and pressure. This chapter is based on a worldwide analysis of geological inventory of coal resources, reserves, production, and consumption. The chapter also takes into consideration the development of coal commodity markets with respect to global and regional export, import, and consumption of fossil fuels. Global statistics indicate that coal provides around 30% of international primary energy needs and generates about 41% of the world's electricity. The international coal market has recently reshaped mainly due to large energy demand in China and India, both of which are major coal producers and consumers. The coal production trend is expecting some variation due to changes related to *shale gas revolution* and environmental restrictions, which have made coal a less competitive option, particularly in the energy sector. In the United States, coal demand dropped by 4% in 2011 and 11% in 2012, with many power plants using coal shutdown or converted to natural gas. Despite that, a significant drop in coal domestic demand in the United States was partially compensated by increasing the coal export to China and other countries in the Asian market. These changes, although not directly linked, have had a huge impact on the pricing of coal in global market. The total coal production worldwide reached a record level of 7831 Mt (million tons) in 2012, increasing by

2.9% when compared to the previous year. Currently, coal trails oil as the second most important fossil fuel, with primary consumption energy share of about 30%.

The environmental impact of the coal industry will continue to play a decisive role in the demand for coal worldwide, where the governments are expected to take actions to restrict greenhouse gas emissions and to control issues related to land use and waste management. An important factor in the future of coal will be the introduction of clean coal technologies that can increase efficiency and reduce gas emission. This will require significant efforts and realistic options for future research and development.

2.1 WORLDWIDE ENERGY RESOURCES AND ROLE OF COAL

The conventional (i.e., fossil fuels) and unconventional (i.e., nuclear, hydraulic, and renewable) energy resources around the world are still undergoing continuous change. However, the unconventional ones are still limited at a global scale; thus, changes are slow and barely visible. When the global energy markets are discussed, two main aspects are always considered: the energy source and its impact on environment. The selection of energy source depends on the geographical location, economic situation, availability of resources, and security of supply (political considerations). The environmental concerns related to gas emissions and global warming are forcing the world to move away from fossil fuels (McCarthy and Copeland 2012; Venkatesh et al. 2012; Rana et al. 2013). Therefore, the price of an energy source today is not only based on its energy density or heating value but also based on its environmental impact.

Energy consumption is an authentic human development index that measures a country's achievements in basic aspects of human development (i.e., longevity, literacy, and living standards). Considering the importance of energy to human development, various sources of energy were attempted to explore the possibility of using their calorific values. Generally speaking, fossil fuels (coal, natural gas, and oil) have been widely used in power generation for many decades mainly due to their relatively low cost and high-quality attributes. Hence, fossil fuels today account for 80% of global primary energy consumption (BP 2014a; BP 2014c). Although the global demand of energy continued to increase, the relative weight of various energy sources keep slightly shifting because of economic recession or political instabilities. Apart from other sources of energy, fossil fuels are likely to continue their domination and grow in the future, as illustrated in Figure 2.1. Within fossil fuels, coal is clearly the fastest growing source of energy, where its demand has increased to 38% between 2005 and 2013 and is expected to further increase to 73% by 2030 (BGR 2013). Thus, coal is not only among the world's fastest growing sources of energy but also considered as the principal fuel for generating electricity in many parts of the world, satisfying almost 41% of electricity worldwide as shown in Figure 2.2. In addition, coal is the most abundant among fossil fuels and their large reserves make it a possible candidate to meet increasing energy demand of the global community. However, an increase in coal consumption has a major shortcoming related to global warming, where coal is currently responsible for 43% of the overall CO₂ emission as shown in Figure 2.2 (IEA 2012a).

Apart from their importance as energy sources, coal and other fossil fuels remain one of the biggest dilemma from an environmental point of view (Kharecha et al. 2010; Singh 2011; Bloch et al. 2012; IEA 2012; Ruhl et al. 2012; EIA 2013a, 2014a, b; Govindaraju et al. 2013). However, satisfying energy

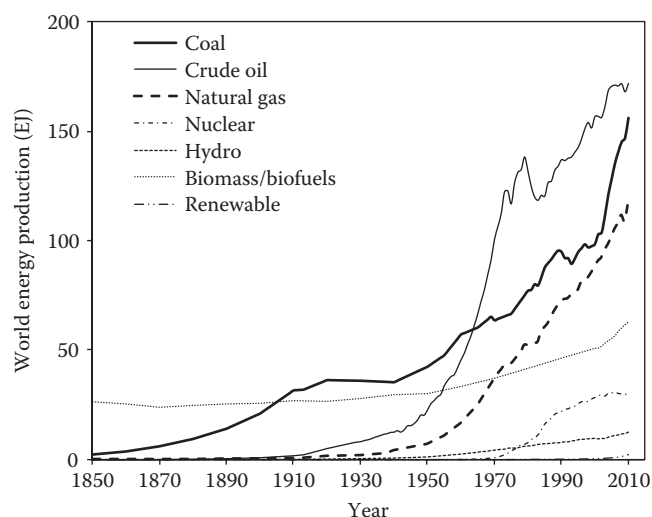


FIGURE 2.1 Worldwide energy production as a function of fuel and time (1850–2010). (Data from IEA, *World Energy Outlook 2013*, IEA, Paris, France, 2013a.)

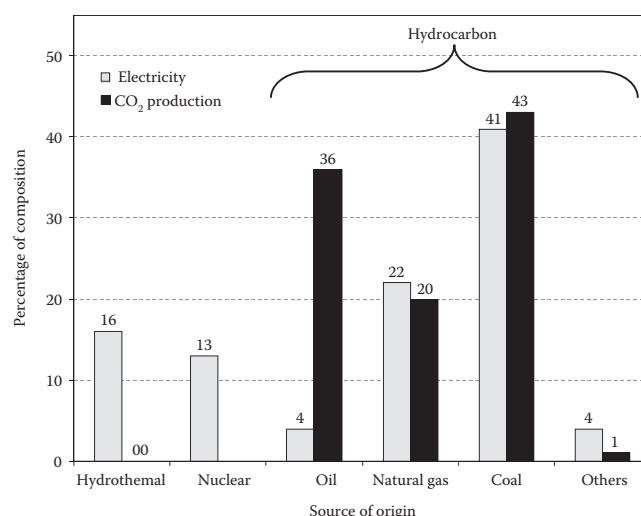


FIGURE 2.2 Worldwide percentage composition of electricity and CO₂ production as a function of source. (Data from IEA, *Coal Medium-Term Market Trends and Projections to 2017*, http://www.worldcoal.org/bin/.../global_coal_market_price_01_06_2009.pdf, 2012a; IEA, *Technology Roadmap: High Energy Efficiency, Low Emissions Coal-Fired Power Generation*, IEA, Paris, France, 2012b.)

requirements, particularly for industrial activities, without fossil fuels in the near future is almost impossible (Mohr et al. 2009, 2013; IEA 2013c; BP 2014a). Thus, the environmental impacts, especially coming from carbon dioxide (CO₂) emissions, should not be overlooked. CO₂ emission coefficients for various types of fuel are reported in Figure 2.3.

The worldwide energy demand is likely to increase at a rate of 10% to 15% every 10 years. This will subsequently raise the CO₂ emissions to around 50% by 2030, when compared to the current level of emissions (IEA 2013d; EIA 2013a). Developed or industrial countries such as North America, Europe, and the Organization for Economic Co-operation and Development (OECD) Pacific countries (Australia, New Zealand, Japan, and South Korea) contribute to the increase in emissions by 70% when compared to the rest of the world. More than 60% of these emissions come from power generation and other industrial sectors. The OECD Pacific countries have high per capita energy consumption in common, and have emission reduction obligations under the Kyoto protocol except South Korea (Jinke et al. 2008).

In order to satisfy the energy requirement, the use of fossil fuels is projected to represent 88% of world's energy consumption at the end of 2030 (BP 2005, 2013, 2014a, b). Therefore, the demands for oil, natural gas, and coal are expected to increase by 1.6%, 3%, and 2.5%, respectively, every year (EIA 2013b). From 2000 to 2012, global coal consumption grew from 4,762 to 7,697 Mt. This represents a 60% growth or a 5% average growth per year (IEA 2012b). This substantial growth in coal demand was mainly attributed to the rapidly growing economies in China and India.

Despite the worldwide economic recession in recent years, both China and India have been among the fastest growing economies for the last two decades. From 1990 to 2010,

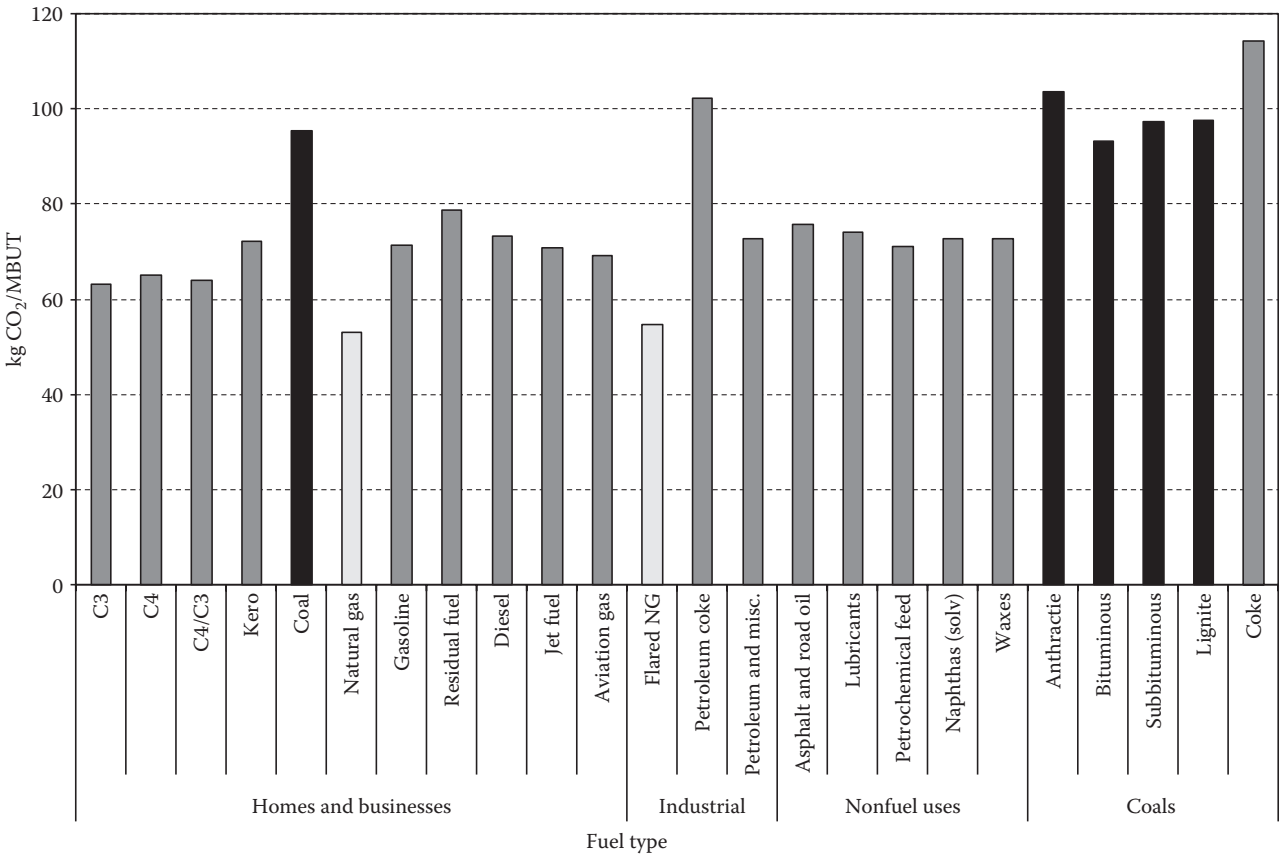


FIGURE 2.3 Carbon dioxide emissions coefficients by fuel. (From EIA, *Carbon Dioxide Emissions Coefficients by Fuel*, http://www.eia.gov/environment/emissions/co2_vol_mass.cfm, February 14, 2013a.)

China's economy grew by an average of 10.4% per year, while that of India's grew by 6.4% per year (Li et al. 2008, 2012; Pfeifer 2013). In both countries, coal played an important role in generating energy and sustaining development. Although the economic growth in both countries slowed in 2012, where the gross domestic product (GDP) declined 7.2% and 5.5% for China and India respectively, their demand and consumption of energy will continue to increase. In the near future, world's growth in energy consumption is expected to rise by an average of 3.6% per year. That growth rate is expected to be around 4.7% for non-OECD regions and 2.1% for OECD regions as shown in Figure 2.4 (EIA 2013b).

The global annual energy demand in 2013 enhanced the economic growth about 2.8%, the energy consumption by 2.1% (10.7 GToe), along with 2.0% (26.1 GtCO₂) increase in CO₂ emissions (Hook 2010; Patzek and Croft 2010; IEA 2012a). This demand in energy is anticipated to further increase in the coming years and will eventually reflect on fossil fuel demand. The recent forecast indicates that between 2012 and 2018, the expected yearly average rate of growth in coal demand is around 2.3%. This rate is relatively lower than the previously mentioned average growth rate between the years 2000 and 2012, which was 4%. Despite that, coal will still be one of the main driving forces in the economic growth of developing countries, mainly China and India. The importance of coal to human prosperity and development has made it a truly global

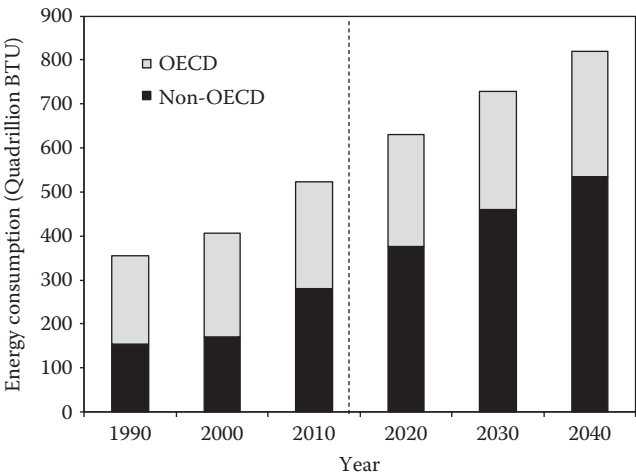


FIGURE 2.4 World energy consumption, 1990–2040. (Data from EIA, *International Energy Outlook 2013 with Projection to 2040*, Washington, DC, [http://www.eia.gov/forecasts/ieo/pdf/0484\(2013\).pdf](http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf), July 2013b.)

industry, where it is commercially mined in more than 50 countries. Figure 2.5 illustrates the top countries in the world that heavily rely on coal for electricity generation while Table 2.1 illustrates the approximate values of coal energy sources and equivalent conversion factors and their calorific values.

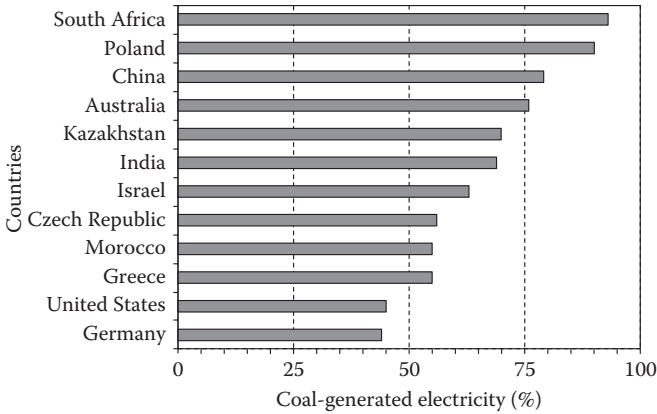


FIGURE 2.5 Worldwide top countries that use coal as a major source for electricity generation.

TABLE 2.1
Approximate Values of Coal Energy Sources and Conversion Factors

Energy Equivalent Conversions or Calorific Values	
1 ton of coal equivalent =	0.7 ton of oil equivalent
1 exajoules [XJ] =	34120842.37 ton of coal equivalent (TCE)
1 kilojoules =	1.0E-15 exajoules
1 exajoule [EJ] =	1018 J = 278 × 109 TWh = 34.1 × 106 t TCE
1 cal =	0.003967 BTU = 4.184 J
1 BTU =	1.0550559E-15 XJ
1 TCE =	0.70 toe = 770.7 m³ natural gas = 29.3 × 109 J
1 kcal =	0.0041868 megajoule (MJ)
1 short ton =	25.18 MBTU
1 short ton =	26.57 gigajoule (GJ) = 2896.13 joule
1 MBTU =	106 BTU (IT) = 0.111836 MJ
1 BTU (IT) =	1055.06 joule = 0.001055 MJ
1 ton of coal (equiv) =	29.3 GJ = 27.8 MBTU
1 ton of coal (equiv) =	26.6 GJ = 25.2 MBTU
1 lb coal (anthracite) =	12,700 BTU
1 lb coal (sub-bituminous) =	8,800 BTU
1 lb coal (bituminous) =	11,500 BTU
1 million BTU =	0.94782 giga (10⁹) joules
1 million BTU =	27.778 metric ton of coal equivalent (TCE)
Mass Equivalent Conversions	
1 short ton =	1.12 long ton
1 long ton =	1.016 metric ton
1 short ton =	0.9072 metric ton
1 ton =	0.9842 UK long ton
1 metric ton = ton =	1000 kg = 2204.6 lb = 1.1023 short ton
1 ton =	2204.62 pounds (lb)
1 ton =	1.1023 US short ton

2.2 COAL TYPES AND CLASSIFICATIONS

Coal is basically the hydrocarbon material that transforms from one phase to another under certain conditions during long period of time through a process known as *coalification*.

Coal usually has a high content of carbon; thus, its physical state is solid and black in nature. Due to the presence of hydrocarbon, coal is widely used as a solid fossil fuel that generates electricity and heat. The heat content of coal depends upon the amount of fixed carbon, which relies on the origin of coal, the aging process, and the formation conditions. The transformation of dead biotic material and vegetal matter to coal passes through different stages, from which various types of coals take shape. The coal formation starts with the peat, the coal precursor, which successively transforms under suitable conditions to lignite, sub-bituminous, bituminous, anthracite, and finally graphite. Temperature plays a very important role in converting coal from one phase to another. For example, an increase in temperature causes peat to convert to lignite, a soft, low-rank coal. A further increase in temperature transforms the lignite into sub-bituminous, bituminous, and then into anthracite, which is the highest rank of coal.

As previously stated, coalification is defined as the degree of change that coal undergoes as it matures from peat to anthracite. The degree of coalification determines the coal’s physical and chemical properties. Based on these properties, different types of coal are classified today into mainly two categories: *soft or low rank* and *hard or high rank*. Coal ranking primarily reflects the degree of progressive alteration in the transformation from lignite to anthracite; therefore, the primary two ranks of coal can be further divided into different classes (Parr 1928; Krishnan 1940; Wood et al. 1983). Low-ranking coal represents about 47% of global coal reserve, while high-ranking coal represents 53%. Low-rank coals, which include lignite (17%) and sub-bituminous (30%), are typically soft and friable with a monotonous look (World Coal 2015). The high-rank coals, on the other hand, are generally shiny hard black solid, and they include bituminous (52%) and anthracite (1%). High-rank coals have more carbon and, therefore, higher heat value than the low-rank coals. The high-rank coals are also characterized by lower moisture content when compared to the low-rank coals. Anthracite is on top of the coal rank and correspondingly, has the highest carbon and energy content and the lowest level of moisture. Bituminous, which is the most abundant high-rank coal, is normally divided into thermal and metallurgical coals. Thermal coal is also known as *steam coal* and is frequently used in power generation and cement manufacturing. The metallurgical coal, on the other hand, is sometimes named *coking coal*, and it is industrially utilized in iron and steel manufacturing. The United States is an example of a country that produces different types of coal, where U.S. coal production consists of 7.8% lignite, 44% sub-bituminous, 48% bituminous and 0.2 anthracite.

Table 2.2 illustrates the properties of the different types of coal (Krishnan 1940; Wood et al. 1983), including their calorific value. Anthracite is almost hydrogen-free coal with the highest energy content of +30 MJ/kg. Bituminous coal contains small amounts of hydrogen and water and its energy content ranges between 18 and 29 MJ/kg (Krishnan 1940; EIA 2013c, e, 2014b). Sub-bituminous and lignite, in contrast, have comparatively lower heating values of 8 to 25 MJ/kg and 5 to 14 MJ/kg, respectively. The heating values of the coal types

TABLE 2.2
Coal Classifications and Properties

Type of Coal	Fixed Carbon (%)	Volatile Matter (%)	Moisture (%)	Calorific Values (MJ/kg)	Physical State/Uses
Low-Rank Coal, 47%					
Peat	<50	10–12	60–85	6.69	Low energy level Subject to bacterial and fungal action
Brown coal	–	–	40–60	8.0	Water squeeze out
Lignite (17%)	65–78	40–50	35–50	5–14	Hard and massive, largely power generation
Sub-bituminous (30%)	–	–	20–30	8–25	Hard and brittle
Hard Coal, 53%					
Bituminous (52%)	60–80	–	41	18–30	Soft and shiny
High volatile bituminous	–	>31	32	32.2	–
Medium volatile bituminous	–	22–31	40	35.2	Power generation, cement manufacturing, and industrial uses
Low volatile bituminous	–	8–14	30	35.6	–
Semi-anthracite	86–92	8–15	15	36.0	–
Anthracite (1%)	92–98	5–10	<12	30.0	Very shiny domestic/industrial smokeless fuel
Meta-anthracite	≥98	<2	–	–	Power generation, cement manufacturer, and industrial uses
Thermal (coking coal/steam coal)	43–48	20–36	5–12	25–28	Manufacturing of iron and steel
Metallurgic coal (coking coal)	88–93	20–25	8–12	31–33	Demand by steel producers

suggest that 1 kg of anthracite has the same heating value of 2–6 kg of lignite. Although the different types of coal are classified into two categories as stated previously, these types sometimes overlap and the energy content of the specified coal is not always apparent and can vary within a broad range.

In addition to calorific values, the quality of coal also depends on its composition, which is a typically conventional composition of organic compounds that is made of fine and coarse aggregates, carbon, hetero-elements, and other chemicals as shown in Figure 2.6.

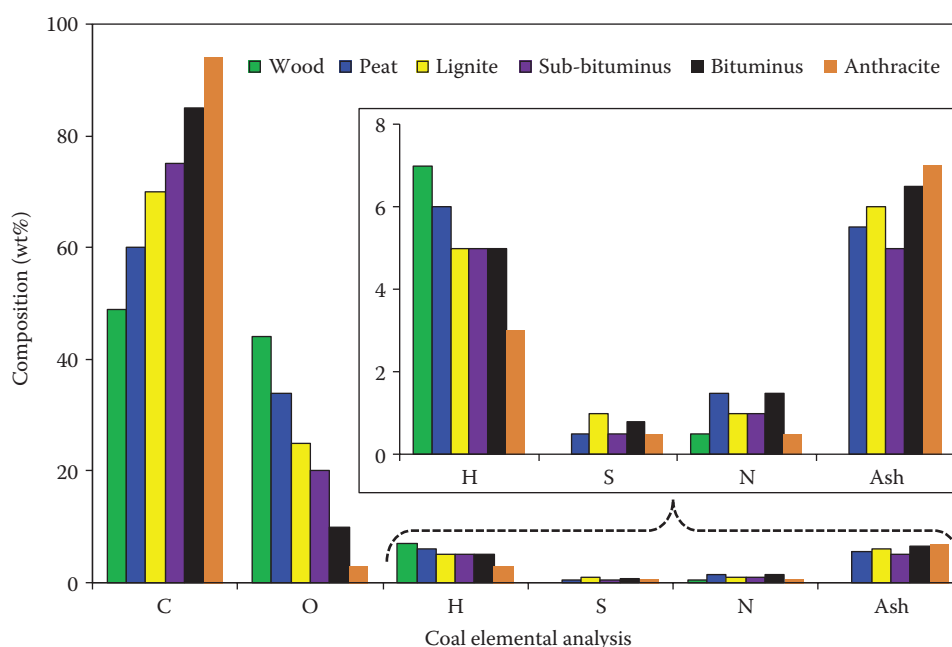


FIGURE 2.6 Average of coal elemental composition.

In the high-rank coal (i.e., bituminous and anthracite), carbon contents tend to increase, while oxygen and hydrogen contents tend to decrease, which consequently lower the oxygen/carbon (O/C) and hydrogen/carbon (H/C) ratios, respectively. The amounts of sulfur and nitrogen in coal, in contrast, do not show any clear tendency against the variation of coal sources or types. Although the value of a coal primarily depends on its rank (high- or low-rank coal), one should not lose sight of the fact that other characteristics have an impact on its utilization, such as the content of trace elements (S and N), ash content, moisture, and volatile hydrocarbon. Metallurgical coal is primarily used in steel industries, while steam coal has application to generate electricity and heat to produce steam used in industrial processes.

2.3 WORLD COAL RESERVES AND RESOURCES

Coal is one of the oldest known fossil fuels used. The United Kingdom issued the first analysis of coal reserves in 1871, followed by the U.S. reserves analysis of Pennsylvania anthracite fields in 1926 (Harnsberger, 1919; Avrtitt 1975; Grubert 2012; BP 2013; Milici et al. 2013). The first comprehensive survey at the world level was The Coal Resources of the World, produced in 1913 for the 12th World Geological Congress (Avrtitt 1975; Wood et al. 1983). After World War I, surveys were continued by the World Power Conference, which is now called the *World Energy Council*. The World Energy Council published its latest (23rd) survey in 2013.

Based on the definition, coal resources correspond to the estimated amounts of coal that are believed to be physically contained in a certain place, at a given time. The extraction of this coal might not be technically viable or economically feasible, but is geologically possible. Coal reserves, on the other hand, refer to the estimated amounts of coal that can be feasibly exploited using existing technologies. The developments taking place in coal extraction technology has a significant impact on coal reserves. Recent report shows that the global coal reserve has

increased by more than 100%, particularly in China and India (Lester and Steinfeld 2007; EIA 2013b; IEA 2013b; Pfeifer 2013; BP 2014b). Although there are several predictions for world-wide coal reserve by major institutes such as British Petroleum (BP), International Energy Agency, Energy Information Administration, and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), inconsistent data are still found in the literature due to the difficulty associated with accurately estimating the amount of coal in underground (Fettweis 1976; BGR 2009; BP 2013; EIA 2013c; Rutledge 2013).

However, considering the rapidly increasing trend in coal reserves and the continuous development in mining industry, one might suggest that the actual coal reserve is much higher than the one currently reported. The reserves and resources of hard coal and lignite are adequate to cover the foreseeable demand for many decades from a geological point of view. Coal boasts the largest potential of all nonrenewable energy resources (BGR 2013) with a share of around 56% of reserves and 89% of resources as shown in Table 2.3.

Coal is uniformly distributed throughout the world as depicted in Figure 2.7. Proven coal reserves are present in 70 countries (Fettweis 1976). Countries with top proven coal reserves are shown in the Figure 2.8. A comprehensive regional coal distribution by type is shown in Figure 2.9. The figures show that around 28% of global coal reserves are located in North America, mainly in the United States. More than 34% is present in Europe and Eurasia, dominated by Russia followed by Kazakhstan and Ukraine, and approximately 31% is located in Asia Pacific, mainly China, India, and Australia.

In 2013, the EIA has estimated that the United States has about 481 billion tons of coal reserve, which is larger than the remaining natural gas and oil resources (EIA 2013d). Africa and the Middle East's share of coal reserves vary between 4% and 8%, while South America holds 2% of world reserves (BP 2014b). As previously stated, these statistical data are not absolute and there are some discrepancies in the literature about them. The discrepancy in data can be attributed to

TABLE 2.3
Worldwide Regional Distribution of Reserves and Resources of Non-Renewable Coal Fuels, 2012

Regions	Hard Coal (Mt)			Lignite Coal (Mt)		
	Reserves	Resources	Percent Use	Reserves	Resources	Percent Use
Europe	19,452	470,429	4.1	70,134	325,038	21.6
Commonwealth of Independent States	130,362	2,839,068	4.6	93,065	1,278,553	7.3
Africa	36,210	81,438	44.5	66	402	16.4
Middle East	1,203	40,000	3.0	na	na	na
Australasia	342,917	6,891,042	5.0	81,884	1,054,481	7.8
North America	229,914	6,645,013	3.5	32,912	1,486,144	2.2
Latin America	8,943	26,491	33.8	5,073	20,118	25.2
Antarctica	0	150,000	0.0			
Rest of the world	768,999	17,143,481	4.5	283,134	4,164,736	6.8

Source: BGR (Bundesanstalt für Geowissenschaften und Rohstoffe/German Federal Institute for Geosciences and Natural Resources), *Energy Study 2013, Reserves, Resources and Availability of Energy Resources*, BGR, Hannover, Germany, December 2013.

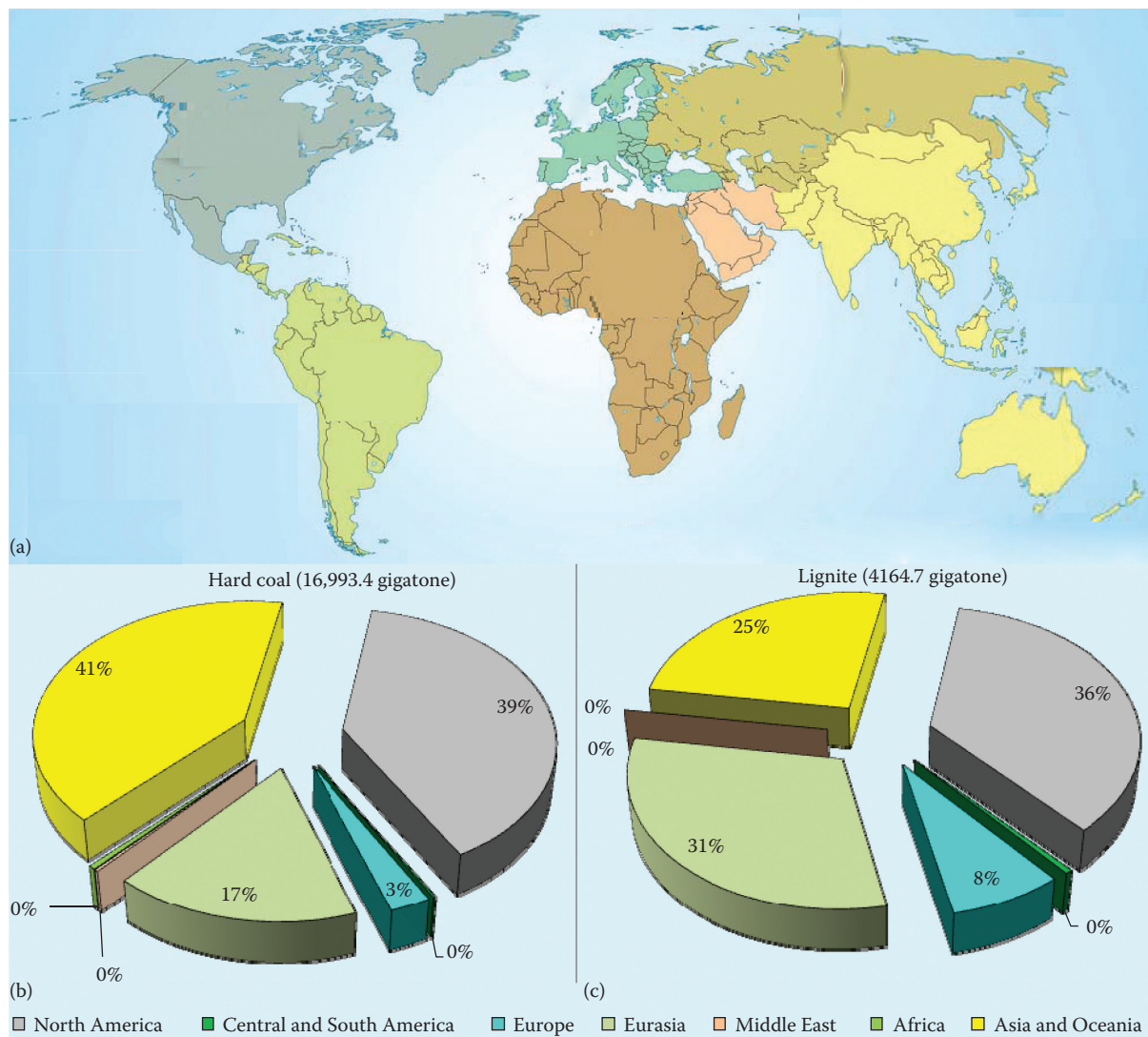


FIGURE 2.7 Worldwide distribution (a) of hard (b) and lignite (c) coals.

various factors such as the difficulty associated with accurately estimating the amount of coal in underground, the variation in update to statistics data, and the inconsistency in region's definitions as in the case of Eurasia and Asia Pacific. In addition, one should also take into consideration the overlap between the coal types, where, for example, sub-bituminous coal is frequently referred to as *black lignite*. Thus, the low-rank coal (sub-bituminous and lignite) is sometimes called *lignite*.

The top 10 countries that have the largest hard and lignite coal resources and reserves are shown in Figures 2.10 and 2.11, respectively. On a regional basis, many European countries reduced their hard coal reserves by 25% to 35% over the past few decades. For example, the European lignite reserves have considerably reduced, particularly for Germany, which was the world's largest lignite producer until 1997. Similarly, Poland has reduced its hard coal reserves by 50% since 1997. On the other hand, the Indian and Australian hard coal reserves have substantially increased since 1990 (EIA 2014b).

2.3.1 GLOBAL COAL SCENARIO

Coal plays a unique role in securing the world's energy demand and its resources are more widely distributed in the world compared to oil and natural gas. The role of coal as a principle fuel is expected to increase in the near future because it is less expensive and more available than other fossil fuels (Wolde-Rufael 2010). According to previous studies, coal is expected to be a primary source of energy in the coming 150–170 years, whereas oil and natural gas, roles are expected to end in about 50–75 years (Campbell and Laherrere 1998; BP 2005). However, in the current scenario, the world is not running out of fossil fuel for at least next several decades (Hook and Aleklett 2010; Riazi et al. 2013). Clean fossil fuel burning may be an issue that humanity does face but their (gas, oil, and coal) abundance is not limited to the twenty-first century. The life expectancy of coal reserves is normally determined by the ratio between the proven reserve and the production rate (R/P ratio). North America has the highest

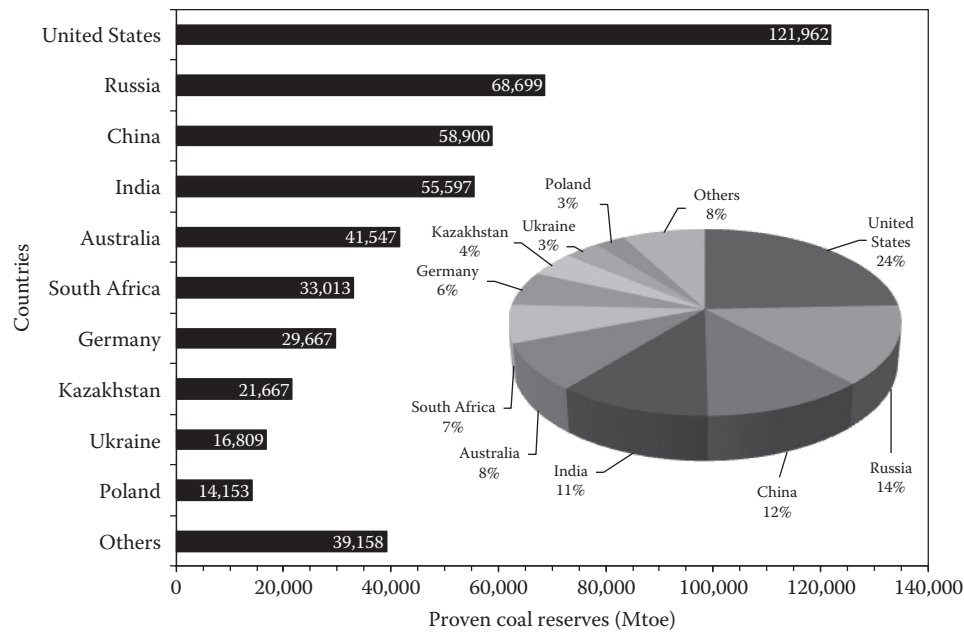


FIGURE 2.8 Worldwide top proven coal reserve. (EIA, 2013.)

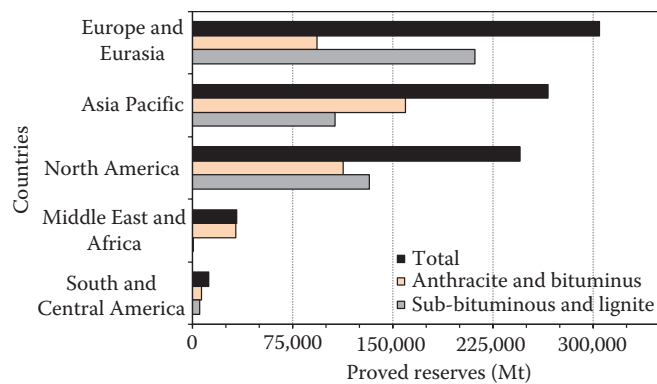


FIGURE 2.9 Worldwide regional distribution of reserves of various coals. (Data from EIA, *International Energy Statistics*, <http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=1&pid=7&aid=1>, 2014b.)

R/P ratio, which is mainly attributed to the individual reserve of the United States. Despite the wealth of available data about coal reserves and resources, both globally and regionally, the quality and reliability of these data are not as good as the ones reported for crude oil and natural gas. Practically speaking, obvious discrepancies are present in the literature and some data are outdated. Over the last two decades, limited resources were reclassified into reserves, despite the enhancement in coal production technology and coal production rate (Figure 2.12).

Similar to oil and gas reserves (Riazi et al. 2013), coal reserves are mainly dominated by a group of countries known as the *Big Six*. These countries are the United States, Russia, China, India, Australia, and South Africa in descending order of reserves (Hook et al. 2010). The United States holds around 25% of global reserves and is considered to be the second

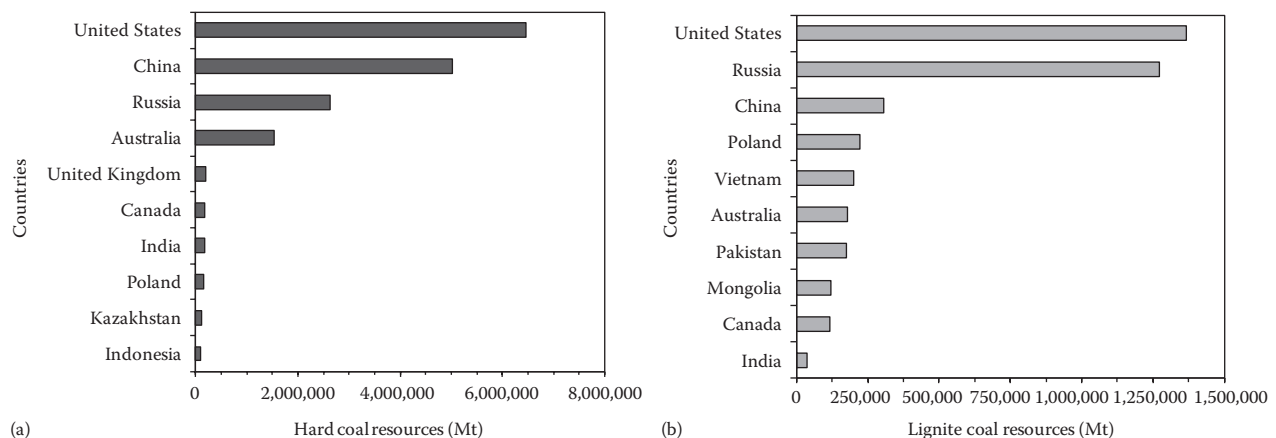


FIGURE 2.10 Top 10 countries, resources for hard coal (a) and lignite coal (b). (Data from BGR (Bundesanstalt für Geowissenschaften und Rohstoffe/German Federal Institute for Geosciences and Natural Resources), *Energy Study 2013, Reserves, Resources and Availability of Energy Resources*, BGR, Hannover, Germany, 2013.)

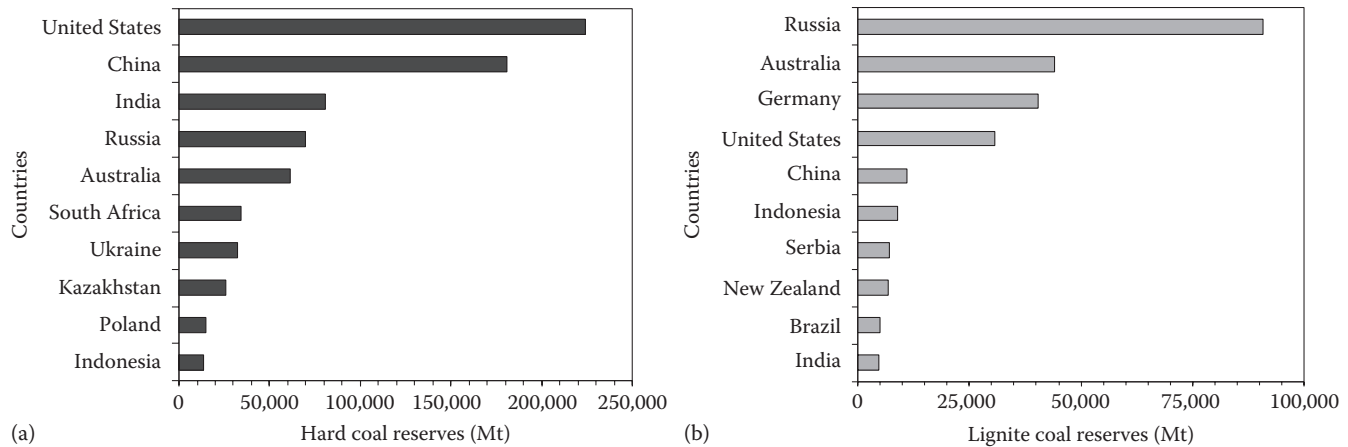


FIGURE 2.11 Top 10 countries, reserves for hard coal (a) and lignite coal (b). (Data from BGR (Bundesanstalt für Geowissenschaften und Rohstoffe/German Federal Institute for Geosciences and Natural Resources), *Energy Study 2013, Reserves, Resources and Availability of Energy Resources*, BGR, Hannover, Germany, 2013.)

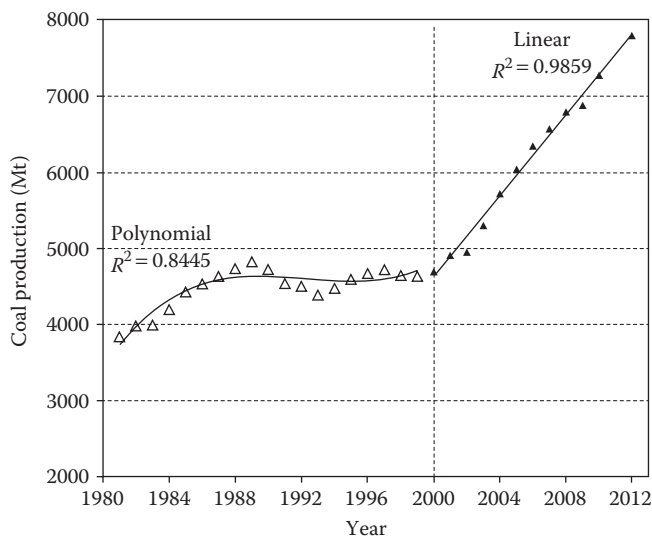


FIGURE 2.12 Worldwide coal production between 1980 and 2012. (Data from BP, *Statistical Review of World Energy June 2014*, <http://www.bp.com/statisticalreview>, 2014b.)

largest producer of coal after China. On the other hand, China is the largest producer of coal, despite the fact that it possesses only 12% of the global reserves. The United States and China together control more than 90% of world's hard coal reserves (Michieka and Fletcher 2012; BP 2013), in addition to their substantial resources of lignite (BGR 2009; BP 2009). The Big Six group currently produces around 80% of the world's coal, with a share of approximately 50% from China. Russia is another major producer that has around 14% of the world's total coal reserve (BP 2009). The BP report indicates that China and India, which have around 12% and 11%, respectively, of world reserves, are of particular interest for the coal industry as they need more inexpensive energy to cope with their rapidly growing economies (BP 2009). Subsequently, in the order, Australia and South Africa have around 8% and

7%, respectively, of the world's coal reserves, and both countries are considered to be significant exporters. The previously illustrated statistical data on coal reserves and resources were collected from BGR Energy, United States Geological Survey, EIA, the BP Statistical Review of World Energy, IEA, and several other sources as reported in the references.

2.4 COAL PRODUCTION

Coal mining has been an important economic activity throughout human history and it continues to be so. Large-scale coal mining and production begun in the United Kingdom more than 200 years ago during the European Industrial Revolution, and gradually spread to other parts of Europe and North America (Hook and Aleklett 2009; Hook et al. 2010). Tower Colliery, in South Wales, is the world's oldest continuously operating coal mine, in operation for about 203 years (1805–2008). Just like other fossil fuels, coal is also created over millions of years in the form of solid hydrocarbon, whose production has depleted or is in decline with time (Thomas 2002; Rodriguez and Arias 2008; Bardi and Lavacchi 2009; Hook and Aleklett 2009). Today, coal continues to be an important energy source, particularly for electricity generation, because of its relatively low cost and abundance when compared to the other fossil fuels.

Although coal reserves are widespread, the largest reserves are limited to a number of countries, notably the United States, China, Russia, India, Australia, and South Africa. The coal production in the United States reached an all-time high of 1175 Mt in 2008, which declined by 1100 Mt from 2009 to 2011 (IEA 2013a). On the other hand, world coal production has increased by 60% since 2002 (Humphries and Sherlock 2013). The cumulative and regional coal production values over the last three decades are shown in Figures 2.12 and 2.13, respectively. Since the beginning of the twenty-first century, coal production has increased severalfold to fulfill the growing demand for energy in the world. Most of the growth in coal consumption came from Asia, particularly China, while coal consumption growth in the OECD region dawdled due