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LECTURE TEXT

Coal: exploration, reserves, and utilization

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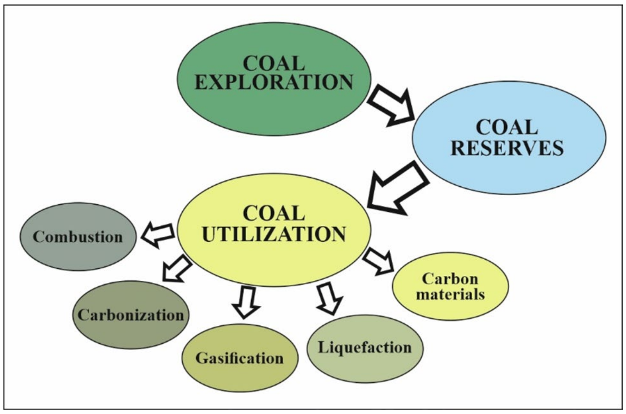
Abstract

Coal exploration is a very demanding task, highly dependent on geological and economic factors and the utilization of coal. This lecture text includes information on a variety of geological techniques used in the exploration of coal and coal-bearing sequences, as well as on the calculation, assessment, classification, and reporting of coal resources and reserves. The main features of coal utilization and some environmental aspects are explained briefly. Special attention is paid to the by-products of coal utilization, their uses, and possible role in a zero-waste strategy.

Graphical abstract



Keywords Coal · Exploration · Resources · Reserves · Utilization · Combustion · Carbonization · Gasification · Carbon materials

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Introduction

Coal is a brownish to black sedimentary rock mostly composed of amorphous organic matter and small amounts of minerals, gases, and liquids. It is used as fuel. The organic matter in coal consists of lithified plant remains originally deposited in the paleomire and converted into coal over time (millions of years) under increased temperature and pressure conditions [1]. The deposited plant remains undergo decomposition and complex physical and chemical changes in the earth, affected by synsedimentary and post-sedimentary influences to produce coals of differing ranks and varying degrees of structural complexity [1, 2]. Sedimentary sequences with coal or peat layers (seams) from the Upper Paleozoic to recent times are found throughout the world. The origin of coal has been studied for over a century, but no one has identified a model that can predict the occurrence, development, and type of coal, or provide a satisfactory explanation for the cyclic nature of coal sequences and the physical and chemical properties of coals [3]. However, sequence stratigraphy has recognized a pattern of different phases of deposition and erosion within coal-bearing sequences.

According to the coalification degree/rank, coal can be divided into lignite, subbituminous coal, bituminous coal, and anthracite [4], with a variety of lithotypes in coals of different ages. Coal mostly consists of carbon (C), with variable amounts of hydrogen, (H) sulfur (S), oxygen (O), and nitrogen (N). The carbon content of coal increases with the rise of the coalification degree. The coal rank is greatly affected by tectonic movements and volcanic activity. Coal rank influences the utilization of coal. Various aspects of coal chemistry (its nature, composition, coking, gasification, liquefaction, and production of chemicals), as well as coal geology (major eras of formation, peatification, coalification, coal types and their properties, coal lithotypes, and coal ranks), are discussed in more detail in a paper previously published in this journal [5].

Geological exploration of coal should determine the location and quality of coal and estimate the resources available in a particular area. The approach has changed and improved over past decades. The next level of exploration needs to identify all the geological factors that will facilitate or constrain mine development. Geological exploration employs many field and laboratory techniques [2, 4]. Field investigations of coal-bearing sequences include mapping and sampling of the surface, surface geophysics, and drilling with sampling. Laboratory techniques include a number of different analyses [6], such as proximate and ultimate analyses; the determination of the chemical composition and thermomechanical properties of ash and the thermal, mechanical, and petrographic properties of coal; and mineralogical and geochemical analyses of coal and interburden sediments. Geotechnical and hydrogeological data [2] are very important as they provide useful information for the estimation of resources and reserves.

Coal is an abundant and low-cost natural resource. Coal rank and the quality and amount of resources and reserves greatly affect the utilization of coal. For more than 200 years coal has been the most important energy source that supported the economic and social development of humankind. Coals of different ranks can be used for electricity generation by combustion [7] and heat, the production of metallurgical coke by carbonization [8], liquid fuels by direct or indirect liquefaction [9], syngas by gasification [10], and chemical products [11], as well as the preparation of functional carbon materials [12–15]. Coal by-products from different processes can be transformed from waste to valuable goods [16].

The mining and exploration of coal starts thousands of years ago in ancient China, the Roman Empire, and other countries, according to documents of early mines. Coal became important goods in the Industrial Revolution first in the UK and few years after in West Europe, North America, and Japan. It provided the main source of primary energy for industry and transportation in industrial areas from the eighteenth century to the 1950s [17]. By the late twentieth century coal was replaced by oil, natural gas, nuclear power, or renewable energy sources in domestic, industrial, and transportation usage. Until 1988, Europe had a leading role in world coal production with 4777.3 million tons (Mt) [18]. Since 1989 Asia Pacific has assumed a leading role in world coal production. In that period, world coal production constantly increased from 4467.2 Mt in 1989 to 8254.5 Mt in 2013 with China as the leading producer and consumer of coal. Total world production declined in the period from 2014 to 2020, but in 2022 it would reach its highest value ever with 8803.4 Mt [18]. Statistical analysis in 2020 showed than global coal consumption in electricity & heat, iron & steel industry, cement industry, and other sectors was 64%, 17%, 6%, and 13%, respectively [19]. In 2022, coal accounted for 27% of the world's primary energy demand [20].

Environmental issues including the health of employees in the coal mining sector, destruction of landfills during mining activities, air pollution, and contribution to global warming connected with coal utilization have been increasingly important since the late twentieth century. World emissions of carbon dioxide from coal follows the coal production growth and increased from 7484.46 Mt CO_2 in 1990 [21] to 12,986.53 Mt CO_2 in 2020 with China, India, and the USA as the biggest emitters. A reduction of CO_2 emissions occurred in 2020 in the UK, Germany, and USA owing to significant use of renewable energy sources.

This paper provides comprehensive information about coal exploration, classification of resources and reserves, utilization of coal, and future trends in coal utilization.

Coal exploration

Coal exploration encompasses a broad range of activities aimed at finding coal-bearing sediments and deposits that can be exploited [2]. The process relies on a variety of geological techniques to determine the location and quality of coal, estimate resources, and identify geological factors that will facilitate or constrain coal exploitation and environmentally acceptable utilization in the future. Coal exploration includes field activities, laboratory work, and estimation of resources and reserves using different software products [2]. The results of field and laboratory investigations are used for three-dimensional modeling of coal-bearing sediments, including estimating the quantity (resources) and quality (grade) of coal and producing a geological report or similar document.

Geological exploration is conducted in several stages. Initial exploration activities begin over a large area, usually one sedimentary basin with a stratigraphic potential for coal-bearing series, and then target increasingly smaller areas. The aim is to determine the most prospective part of the coal-bearing basin for coal extraction and commercial exploitation. Detailed geological exploration activities focus on a small, most prospective area, applying all the techniques and tests necessary for the evaluation of resources, mine planning, and environmental impact assessment of the proposed mining activity. The final geological report, after detailed exploration, represents the basis for subsequent feasibility studies.

Coal exploration, like any mineral commodity exploration, is an intensive and organized process undertaken by companies and/or corporations with suitable experience, after adequate permission is obtained by the authority in charge of exploration. The resource exploration authority allows only exploration activities in or under land, and in water or sea above land, to detect minerals (metals, raw materials, industrial minerals, rocks, coal, oil, and water) and determine their quantity and quality.

Coal exploration programs include several components [22] (with supplements):

- Obtain legal permission to explore the area.
- Evaluate available geological information and compile reliable base maps for further exploration.
- Carry out surface exploration (geological mapping, geophysics, etc.) and collect environmental data.
- Conduct subsurface exploration (drilling and underground exploration activities—adits, shafts, tunnels, etc.).
- Sampling and analyzing coal and other rocks.
- Collect all data, generate a database, compile all information, develop a three-dimensional model, and evaluate coal resources and reserves using modifying factors.
- Prepare a geological report.

Field techniques

Field exploration of a coal-bearing basin is an essential part of any exploration program, especially the identification and assessment of a new potential area. It includes field mapping, interpretation of satellite imagery and aerial photos, and surface and underground geophysical studies [23]. Basic geological maps, interpretations of satellite and surface images, and previous reports provide initial information about the geological and structural settings of areas planned for exploration. In most countries, all of this information is usually available from the Geological Survey or other competent authority. Published scientific papers related to the specific area are also very helpful.

Field examination of coal seams, as well as interburden and overburden sediments, is the first step. It provides significant information for planning of the drilling program. The lithological description of the coal and lithological types associated with the coal and coal-bearing sequences is of great importance in field examinations. Special attention needs to be dedicated to the mapping of outcrop coal seams, faults, tuff horizons, and igneous intrusions. Outcrop coal seams are usually weathered and oxidized, and they have different properties. Their quality also differs from that of deeper seams. The recognition and examination of marker horizons, such as limestone, sandstone, or beds containing fauna or floral assemblages, or tuff horizons, are very important for correlating coal seams and facies patterns and identifying faults. Igneous intrusions and hydrothermal fluids have altered coal and caused fast carbonification-aromatization of coal and the formation of new minerals, in some cases with high concentrations of potentially toxic trace elements.

The aim of field exploration is to determine the location and lithology of coal seams and associated rocks in coal-bearing sequences, as well as the structural features, igneous intrusions, and hydrothermal influences, along with collecting fresh samples for laboratory testing. If geological information is already available on the area of interest, then fieldwork first focuses on the verification of previous coal seam data and taking a new fresh sample to eliminate possible omissions in previous examinations.

Drilling

Drilling is a base method used in exploration. It provides information about the coal seam thickness, coal quality, and lithology of the sediments and rocks associated with the coal [2]. Core drilling is the most often used drilling method in coal exploration. It consists of drilling of a cylindrical core that forms part of a component. Drilling is carried out with specific equipment and can be accomplished by rotary rigs or diamond drill rigs. After drilling, the core is stored in core boxes (Fig. 1), usually made of metal or plastic (previously in wooden boxes). The boxes are labelled with the borehole number and depth indicator. The next step is photographing the core with its depth indicator and placing it in polyethylene bags to preserve the moisture content and protect the coal from oxidation before sampling. Core recovery through a coal seam and/or coaly series should be at least 95%, but preferably more.

Vertical boreholes are usually drilled because coal seams are mostly subhorizontal or even almost horizontal. However, in the case of a steep coal seam or layer, inclined boreholes will provide more representative data.

One of the most important steps in geological exploration, unfortunately sometimes underrated, is very precise sedimentological logging of the core as it is the basis for future interpretation of issues that always occur during exploration.

Challenges during geological exploration

The challenges encountered during exploration may be classified as geological or technical. The usual geological issues are [24]:

1. Irregular coal seam or layer inhomogeneities, at the contact with either underlying or overlying sediments (Fig. 2a, b), depending on the sedimentological conditions at the beginning of peat formation; parallelization of coal layers, particularly considering possible stratification of layers (Fig. 2c), and different intensity of peat (Fig. 2d1) and sediment compaction (Fig. 2d2), are also important issues, especially if the vertical scale was exaggerated, which was popular before computer software was introduced. All these issues require a denser borehole grid for an adequate level of geological knowledge about the deposit.
2. Subsequent erosion of part(s) of the coal seam or layer by surface streams or groundwater flow (Fig. 2e, f). Geophysical exploration is recommended if very precise sedimentological logging indicates potential erosion, as a dense borehole grid is usually not enough for the best interpretation. A very dense grid means higher costs.
3. Intensive tectonics (Fig. 2g, h) are always an exploration and interpretation challenge, which in most cases requires geophysical methods during exploration.

Technical issues are usually caused by previous coal exploitation, particularly if it took place when detailed maps were not produced on a regular basis. Old tunnels, shafts, and other underground rooms are the greatest obstacles, which can be a considerable problem if their position is not well mapped or even known (Fig. 3).

Fig. 1 Borehole core in wooden box (photo by D. Životić, 2005)

Other data collection

Geophysical data

Geophysical data help determine the subsurface geological structure and spatial location of mineral deposits in the Earth's crust. Coal layers are usually partially or completely covered by other rock units, so the application of geophysical methods that provide information about the subsurface is necessary. The obtained geophysical data provide a sound basis for designing the optimal position and amount of exploratory drilling, which may significantly reduce the cost of exploration. Boreholes provide more precise and more diverse information than geophysical data. However, on the basis of that information alone it is very difficult to determine the structure of the explored area as a result of limited reach. The connection of point, one-dimensional well data with geophysical data provides more abundant spatial information about the structure of the investigated terrain, which is highly significant in complex geological relationships. Geophysical investigations of coal are usually carried out to define the geological structure, locate and outline coal seams, characterize coal deposits, and address

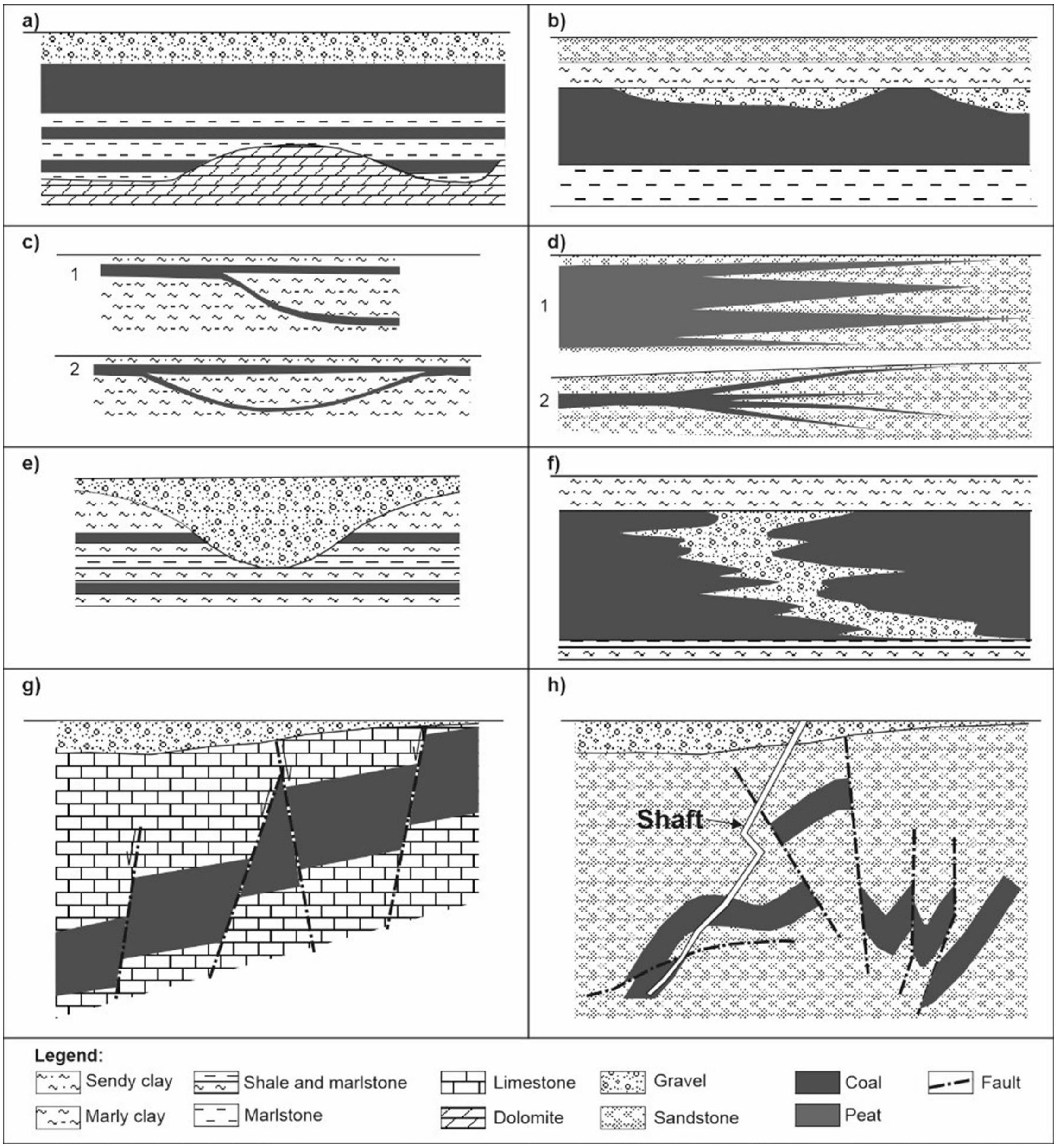


Fig. 2 Geological challenges during exploration (adapted form source [24]); Irregular coal seam or layer inhomogeneities at the contact with underlying sediments (**a**), or overlying sediments (**b**). Parallelization of stratified coal layers (**c**). **d** Different intensity of peat (1) and sediment compaction (2). Erosion of part(s) of coal layer(s) by surface streams (**e**) or underground water courses (**f**). Intensive tectonics influences exploration and interpretation of coal seams (**g**, **h**)

problems associated with the stability and safety of open pit and underground coal mines [25].

Geophysical methods are based on the study of existing natural and artificially created physical fields in the Earth's interior. Natural fields are studied by the gravimetric method (gravitational field of the Earth), magnetic method (Earth's magnetic field), and some of the electrical methods that use the existing electric field (self-potential method, telluric and magnetotelluric method). With other geophysical methods, artificial fields (energy or force) are introduced into the subsurface and the phenomena created by their action are observed. Thus, in the electric and electromagnetic methods, a direct current field and an electric and/or magnetic field are often used, respectively. On the other hand, in seismic research, an explosion in the subsurface or an impact on the Earth's surface generates elastic (seismic) waves that pass through the rocks, and their amplitude and time of arrival are measured. Also, each of the geophysical methods is specifically related to certain physical properties of rocks (density, magnetic

Fig. 3 Remains of previous underground exploitation, Field B of the Kolubara Coal Basin, Serbia (photo by V. Simić, 2006)

susceptibility and remanent magnetization, electrical permeability, speed of propagation of seismic waves, radioactivity, etc.).

The basic task of geophysical methods is to determine the boundaries of mediums between which there is a measurable difference in physical properties and to detect geophysical anomalies. If the Earth's crust was homogeneous in terms of physical properties, the distribution of any physical field would be regular ("normal"). However, it is built from a large number of different rocks that form various geological structures, which has led to the physical properties of the Earth's crust being inhomogeneous. These differences in physical properties cause local disturbances and anomalies in the measured fields. Analysis and interpretation of anomalies provides information about the geological structure and composition of the Earth's crust.

As mentioned above, geophysical methods are based on analysis of the distribution of values of certain physical properties of rocks which are related to their geological and petrological characteristics. The detection of coal by geophysical methods is facilitated by the fact that the physical properties of coal often differ significantly from those of the lithological formation in which it is found (Table 1). Coal generally has a lower density, magnetic susceptibility, seismic velocity, and low radioactivity but higher electrical resistivity compared to surrounding rocks in typical coal-bearing sequences.

The difference in the density of rocks, natural and artificial subsurface features, and the surrounding setting is the basis of the gravimetric method. In addition to the mineral composition, rock density is affected by cracking, porosity, pore fluid content, degree of diagenesis, depth, and age, as well as the geological history and tectonic characteristics of the area. Density changes, both lateral and depth wise, are an important parameter in seismic research. Magnetic susceptibility and remanent magnetization describe the magnetic properties of rocks and are the parameters upon which the magnetic method is based. They depend on the content of ferromagnetic minerals such as magnetite, titanomagnetite, and pyrrhotite. Pyrite, which often occurs with coal, has a low magnetic susceptibility and is paramagnetic like most sulfide minerals.

Electrical resistivity is the most important electrical property of rocks. It is a measure of the resistance of a rock to the flow of electric current. Most of the minerals that make up rocks are characterized by high electrical resistance. Electrical resistance also depends on the geological and physical conditions of the medium and is largely influenced by the porosity and cracking of the rocks. As porosity and cracking

Table 1 Physical properties of coals and associated sedimentary, igneous, and metamorphic rocks [26]

Lithology	Density (wet) (g cm^{-3})		Magnetic volume susceptibility ($\times 10^{-3}$ based on SI units)		Electrical resistivity (Ω m)	Seismic velocity (km s^{-1})
	Range	Average	Range	Average	Range	Range
Coals						
Lignite	1.10–1.25	1.19			9–200	
Bituminous coal	1.20–1.80	1.32	–	0.02	0.6–1×10^{5}	1.8–2.8
Anthracite	1.34–1.80	1.50	–	0.02	1×10^{-3}–2×10^{5}	1.8–2.8
Sedimentary rocks						
Sandstone	1.61–2.76	2.35	0–20	0.4	1–6.4×10^{8}	3.6
Shale	1.77–3.20	2.40	0.01–15	0.6	20–2×10^{3}	2.8
Limestone	1.93–2.90	2.55	0–3	0.3	50–1×10^{7}	5.5
Igneous and metamorphic rocks						
Acid igneous rock	2.30–3.11	2.61	0–80	8.0	4.5×10^{3} (wet granite) 1.3×10^{6} (dry granite)	4.0–5.5
Basic igneous rock	2.09–3.17	2.79	0.5–100	25.0	20–5×10^{7} (dolerite)	4.0–7.0
Metamorphic rock	2.40–3.10	2.74	0–70	4.2	20–1×10^{4} (schist)	5.0–7.0

increase, electrical resistivity decreases as a result of the presence of water in the rock. If there is no water in the "cavities" and they are filled only with air, then the electrical resistivity increases.

The propagation velocity of seismic waves is the speed at which a seismic wave is transmitted through the Earth. When propagating through an inhomogeneous medium, seismic waves are refracted and reflected at discontinuities, i.e., at the boundaries of mediums with different elastic properties. The difference in elastic properties of solid materials manifests itself in the form of a difference in the propagation speed of seismic waves. The seismic reflection coefficient determines whether an interface reflects and depends on both density and seismic velocity. Coal seams with a low density and low seismic velocity often have high reflection coefficients and can be identified well on seismic sections.

Radioactivity is the ability of certain chemical elements (radionucleotides) to spontaneously decay and emit radiation. Radioactive materials are found in traces in all rocks. Different rock types have different levels of natural radioactivity. These differences enabled the use of nuclear logging in boreholes for investigations of coal-bearing sequences. Namely, the radioactivity of coals, pure sandstones, and sandstones with a high content of rock fragments and a clay matrix is very low. Siltstones and non-marine shales have low to medium values, while bentonite and marine shale have high radioactivity values due to the presence of potassium in the former and uranium/thorium minerals in the latter.

Geophysical measurements can be performed above the ground surface (airborne measurements), on the ground surface, and below the ground surface—underground and borehole measurements. For that reason, such measurements can be applied in surface and underground mining. Regional prospecting mainly relies on gravimetric and magnetic surveys, along with reflective and refractive seismic and electrical and electromagnetic methods to locate sedimentary basins. On the other hand, for detailed studies related to ground surface and underground coal exploitation planning, high resolution seismic and microseismic investigations and cross borehole techniques are most often used to define and outline zones of different degrees of risk, related to subsidence, landslides, and water intrusions into parts of mine exploitation galleries.

Gravimetric method This is based on the contrast of the densities of rock masses in the Earth's crust. As a result of different distributions of these rock masses, there are areas where anomalies of the Earth's gravity field occur, which are of either high or low intensity. In the former case, the cause of an anomaly is the accumulation of a high-density rock mass near the Earth's surface. In the latter case, it is usually the accumulation of a rock mass of lower density, e.g., a feature composed of a succession of sedimentary layers. The shape and size of the anomaly are a function of the difference in the density of the feature rock material, the shape, and the depth at which it is located.

Magnetic method The presence of magnetite, whose content in rocks varies over a wide range, has the greatest influence on the magnetization of rocks. Igneous rocks have the highest magnetic susceptibility because they can contain a lot of magnetite. The amount of magnetite decreases with the acidity of the rocks, so acidic igneous rocks (granite) have low magnetic susceptibility values. In metamorphic rocks, magnetic susceptibility value varies with the degree of metamorphism. The susceptibility of sedimentary rocks is usually very low. Since basic and ultrabasic rocks contain the largest amounts of magnetite, this method is most often used to examine those rocks and the structures that were formed as a result of their intrusion. For example, if large magnetic anomalies appear in sedimentary basins, that indicates their presence in either deeper parts or the basement of the basin.

Electric method Its application in geological investigations is based on the fact that the intensity and structure of the electric field (of natural or artificial origin) depends on the electrical properties of rocks and their geometric and spatial characteristics (shape, extent, position in the subsurface, dipping, etc.). This method comprises a large number of procedures based on electrical resistance, induced polarization (which is a frequency-dependent change in resistance), or self-potential (ability to generate spontaneously induced electric fields of local character). Electrical conductivity or inverse electrical resistivity is the most important parameter since shales, limestones, and sandstones generally have a lower resistivity than subbituminous and bituminous coal. It is primarily used for detecting local and relatively shallow delineating geologic boundaries, fractures, and cavities (delineate mine galleries).

Electromagnetic method This is based on monitoring the response of the investigated half-space to the propagation of variable electromagnetic waves in a plane perpendicular to the direction of propagation of the waves. An electromagnetic field can be generated by passing an alternating electric current through a small coil with many turns of wire or through a large loop of wire. The frequencies of the variable primary field used in geophysical surveys are usually less than a few 1000 Hz. The transmitter coil generates a primary electromagnetic field, which propagates above and below the ground surface. If there is a conductive medium in the investigated half-space, the magnetic component of the excitation electromagnetic wave will induce eddy currents (alternating current) in that conductor. These eddy currents then generate their own, secondary electromagnetic field, which is registered by the receiver. The receiver also registers the primary field that propagates through the air, so the total output at the receiver is a combination (resultant) of the effects of both fields, primary and secondary. Accordingly, the measured data will differ in both phase and amplitude from the primary, unmodulated field. The degree of diversity of these components provides information about the geometry, size, and electrical properties of the subsurface medium that behaves as a conductor.

Electromagnetic methods include the electromagnetic reflective method known as georadar (ground penetrating radar, GPR). This device detects the characteristics of the rock mass and the geological structure of the half-space or underground objects based on the reflection of high-frequency electromagnetic waves (from 8 MHz to 4 GHz) on the boundary planes of different mediums, where the dielectric constant (permittivity) and conductivity change. Relative electrical permittivity is a measure of a material's ability to become charged when placed in an electromagnetic field. The GPR transmitting antenna emits a signal (electromagnetic wave) via a broadband antenna or array of broadband antennas by a series of short pulses or transmission waves that change their frequency to cover the desired range. The receiving antenna registers those pulses that are not absorbed by the underground medium but are reflected at precisely determined moments in time. The signal reflected from a reflective horizon is recorded after a certain travel time, which depends on the type of material under investigation. Similar to the seismic method, the depth of the reflector (i.e., the surface from which the waves are reflected) can be determined if the propagation speed of the wave (in this case, electromagnetic, radio wave) is known. The resolution of georadar data is high and the ability to distinguish fine details depends on the frequency of the emitted signal and the propagation speed of electromagnetic waves through the investigated half-space.

Seismic method Rapid development of the seismic method in terms of data precision and reliability has led to it becoming the most important geophysical method for coal exploration (Fig. 4). It is applied in different phases of research. On a particularly large scale, it is used for detailed investigations of already discovered deposits, to characterize deposit geometry, collect various geological and geotechnical data, and solve problems of mine stability and safety. A seismic wave is created when a strong impulse is emitted from the ground surface. It passes through the subsurface rock units. As a result of the different speed of propagation through individual units, seismic waves are refracted and reflected at their boundary surfaces, which can be registered on the ground surface as characteristic refractions and reflections. It is precisely on this phenomenon that the seismic method is based, and depending on which waves it measures, refractive and reflective seismic surveys differ. The most important factors that affect the speed of propagation of seismic waves through the Earth's crust are density, mineral composition, depth, geostatic pressure, porosity, and pore fluid content.

The high resolution seismic survey (HRSS) method is often used to define underlying and overlying strata of coal seams, for underground geological mapping (faults, folds, channel sands, coal seams, etc.), as well as to assess tailings and locate regions of shallow groundwater. This method greatly contributes to reducing the number of exploratory boreholes.

Geophysical borehole logging This method involves probing of a borehole column and the area around the borehole using geophysical methods. The aim of geophysical borehole logging is to obtain data about the medium through which drilling was carried out and the medium around the borehole without coring, as well as data that must be determined in situ. Geophysical borehole logging practically provides continuous measurement of specific physical properties of rock units in boreholes using special geophysical well logging devices (Fig. 5). The registered physical parameters are usually indirectly dependent on the petrological and petrophysical characteristics of the rocks. Geophysical

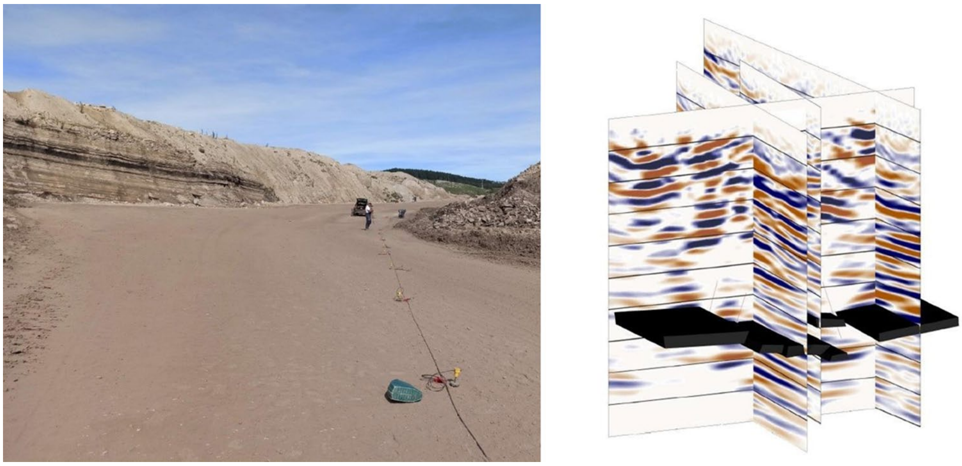


Fig. 4 2D seismic reflection dispositive, open pit Gacko coal mine, Bosnia and Herzegovina (left; photo by S. Arsenović, 2022) and 3D model of coal dram defined by network of 2D seismic cross sections, subbituminous coal deposit Banovići, Bosnia and Herzegovina (right) [27, 28]

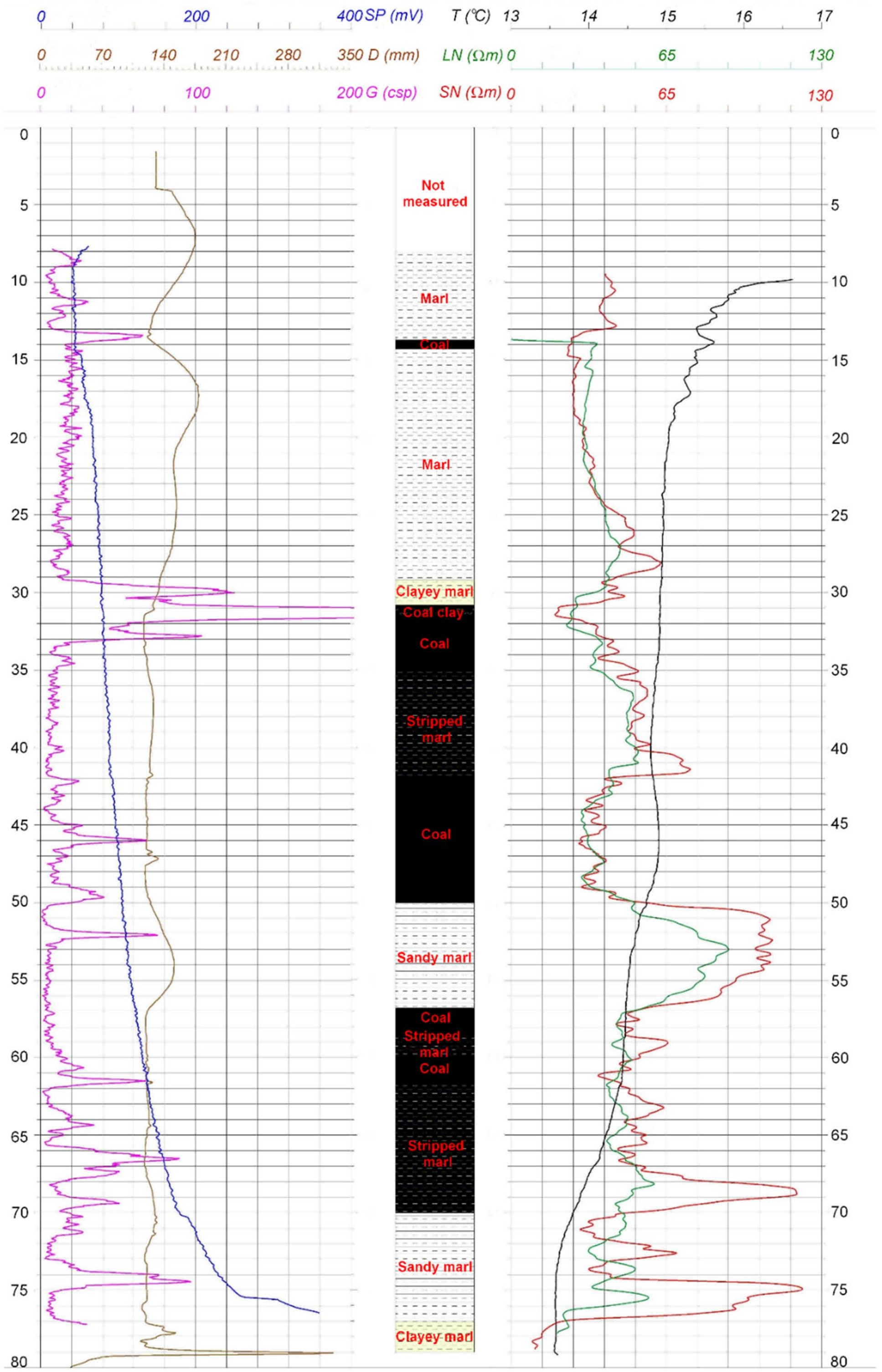


Fig. 5 Geophysical borehole logging at open pit Gacko coal mine, Bosnia and Herzegovina. Borehole logging using the electrical resistance method with short (SN) and long (LN) normal probes, their self-potential (SP), intensity measurement of natural radioactivity (*G*), temperature (*T*), and diameter (*D*) of borehole (device Auslog, D. Nikolić/D. Milošević, Geoing Group d.o.o., 2011)

borehole logging devices are classified as (i) passive, where the physical properties of the formation in the borehole are registered without exciting the formation (self-potential, pressure, temperature, natural radioactivity) and (ii) active, where the formation is excited (electric current, electromagnetic waves, acoustic waves, radioactive radiation) and the effects created as a consequence of excitation are measured. The response of geophysical well logging devices depends on the properties of the formation (lithological composition, rock assembly, geometry of pore space, type of fluid in the rock, etc.), the conditions in the borehole (temperature, pressure, geometry of the borehole, type of mud, thickness of mud cake, depth invasions, etc.), and the device properties (research radius, vertical resolution, stability, etc.).

Although all types of geophysical investigations can be performed in boreholes, electric, nuclear, and acoustic geophysical borehole logging systems play a dominant role in geophysical borehole logging. Electrical well logging systems measure the electrical properties of formations (self-potential well logging, resistivity log, inductive log, dipmeter logs, etc.). Nuclear well logging systems include procedures for measuring the natural radioactivity of rocks and the effects caused by the bombardment of rocks with radioactive particles (gamma ray log, gamma spectrometry log, density log, neutron porosity log, etc.). Acoustic logging systems are based on measuring the speed of propagation of elastic waves through different mediums (acoustic scanning tools, sonic log, etc.). In addition to those listed, temperature logs and caliper logs are also in standard use.

On the basis of borehole logging measurements, the boundaries of rock units and coal seams, their thickness, density, porosity, fluid content and properties, permeability, temperature, etc. can be determined. The borehole logging data makes it possible to evaluate the petrophysical properties of the investigated units (lithological characteristics, porosity, fluid saturation) and create a geological model (correlation, lithofacies analysis, structural and stratigraphic modeling), evaluate the mechanical properties of the formations (Young's modulus, Poisson's number, volume modulus of elasticity and shear modulus), assess seismic parameters (velocity of longitudinal and transverse waves, acoustic impedance, reflection coefficient), and locate zones with abnormal pressures. In geophysical well logging, the size of the area around the examined borehole depends on the well logging system used and is generally considered to be from a few millimeters to several tens of centimeters.

Geophysical investigations are also performed in underground coal mines but as a result of space limitations and safety requirements (especially regarding the use of electrical equipment), only certain geophysical methods are applicable, such as in-seam seismic (ISS) and GPR techniques. Also, gravity measurements can be taken in coal mine galleries to detect faults and voids in underground coal mines.

Geophysical research can provide one-dimensional data (e.g., electrical sounding) and two-dimensional data (seismic refraction and reflection, 2D electrical tomography). However, some of the most modern methods can also produce three-dimensional data (3D reflective seismic, 3D electrical tomography). Likewise, a quasi-2D model can be constructed by merging a series of 1D data, or a quasi-3D model by merging 2D data.

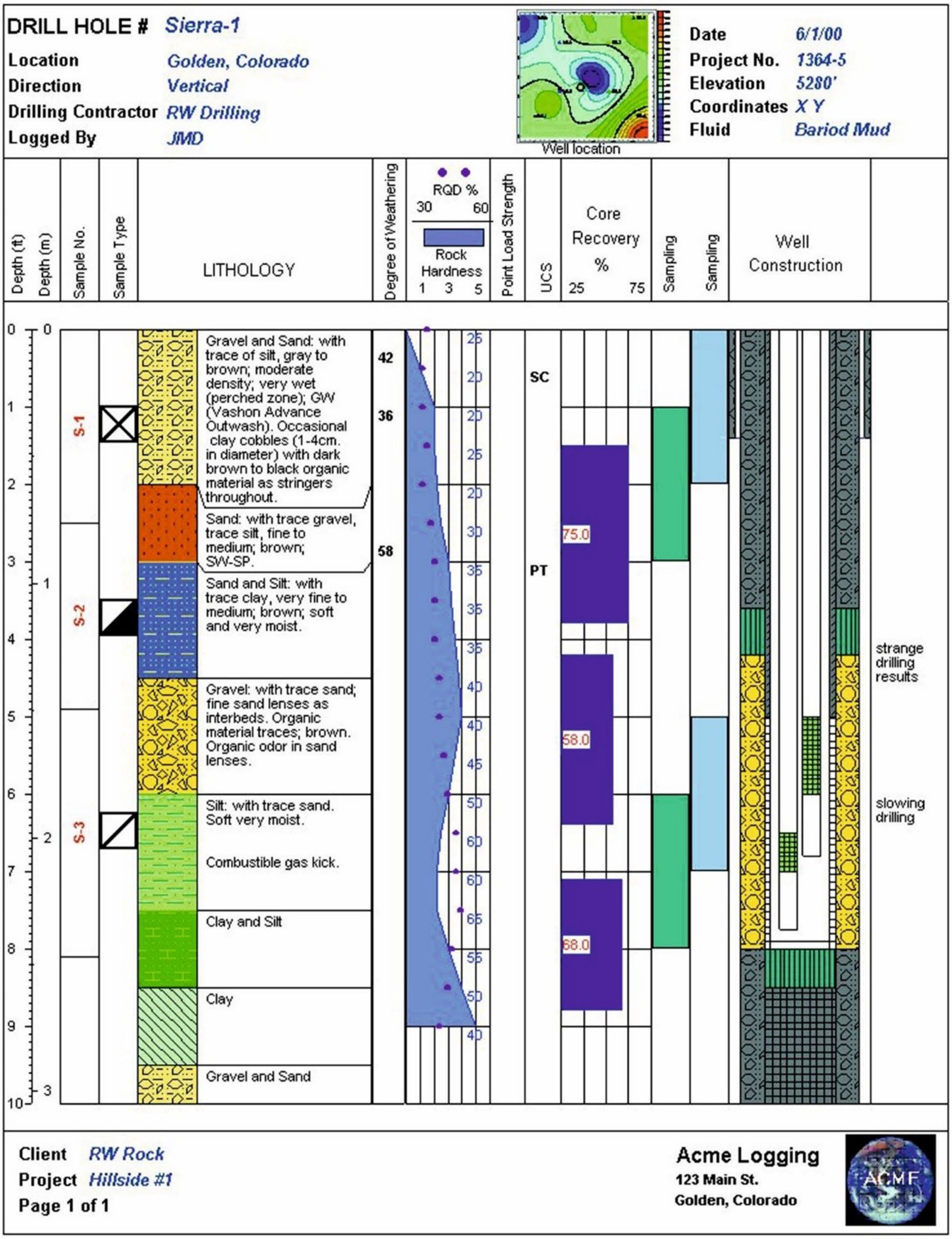
In general, there are two basic principles of interpretation and modeling of geophysical data: direct modeling and inversion modeling. In direct modeling, one starts from a known real physical model (the rock complex) and proceeds towards the unknown response of that model. This means that the physical properties, shape, and position in the subsurface are known for the given model, and the response of that model is calculated, e.g., the response of the anomalies caused by that rock complex. Direct modeling or solving of a direct problem gives a unique solution. By inverse modeling, the parameters of a real physical complex (depth, position in half-space, etc.) are defined on the basis of geophysical measurements of a given physical property. This means that geophysical investigations are carried out with the aim of defining the source of anomalies. In other words, the "unknown" medium is modeled on the basis of measured values, which is the most common case in practice. Several different models are produced by inverse modeling or solving of the inverse problem, which correspond to the measured geophysical data. The ambiguity of interpretation and the number of possible solutions can be limited by combining several different geophysical methods, applying mathematical tools and using all available geophysical, geological, and borehole data.

Geotechnical data

Geotechnical investigations are an integral part of coal exploration and obtaining information on the physical properties of soil, coal seams, and all lithological types associated with coal-bearing sequences. These data are necessary for future exploitation and design of open pit and/or underground mines. Geotechnical investigations include surface and subsurface exploration of an area, along with sampling and laboratory testing.

The cored boreholes drilled during exploration provide a lot of useful information to the geotechnical engineer (Fig. 6). The proposed description of the rock samples includes the following [2]: strength (strong, very weak), degree of weathering (fresh, highly weathered), texture and structure (thick, thin, thinly laminated), color (light, dark, reddish), grain size (fine, medium), name (claystone, siltstone, sandstone), and other properties. The following rock core indices used are [2]: (a) total core recovery (TCR), (b) solid core recovery (SCR), (c) rock quality designation (RQD), (d) fracture spacing index (FI), fracture logging, and rock mass rating (RMR).

Sometimes, geotechnical investigations use the results of geophysical surveys, such as measurement of seismic waves (pressure, shear, and Rayleigh waves) and surface-wave, downhole, and electromagnetic methods (magnetometer, resistivity, and GPR).



DRILL HOLE # Sierra-1
Location Golden, Colorado
Direction Vertical
Drilling Contractor RW Drilling
Logged By JMD

Date 6/1/00
Project No. 1364-5
Elevation 5280'
Coordinates X Y
Fluid Bariod Mud

Gravel and Sand: with trace of silt, gray to brown; moderate density; very wet (perched zone); GW (Vashon Advance Outwash). Occasional clay cobbles (1-4cm. in diameter) with dark brown to black organic material as stringers throughout.

Sand: with trace gravel, trace silt, fine to medium; brown; SW-SP.

Sand and Silt: with trace clay, very fine to medium; brown; soft and very moist.

Gravel: with trace sand; fine sand lenses as interbeds. Organic material traces; brown. Organic odor in sand lenses.

Silt: with trace sand. Soft very moist.

Combustible gas kick.

Clay and Silt

Clay

Gravel and Sand

strange drilling results

slowing drilling

Client RW Rock
Project Hillside #1
Page 1 of 1

Acme Logging
123 Main St.
Golden, Colorado

Fig. 6 Geotechnical logging sheet. Header contains a topographic map with borehole location (with permission from the RockWare Inc [29])

Hydrogeological data

Types of aquifers

Groundwater is any free water in the lithosphere, regardless of origin, physical properties, and chemical, radiological, and microbial compositions [30].

Groundwater can be physically or chemically associated with rock minerals, but free and adhering to the force of gravity and physical laws of fluid flow. A geologic setting, fully or partially saturated with free groundwater, able to store and release groundwater that feeds springs, flows unimpeded to rivers, lakes, and seas, and can be withdrawn by various means of groundwater extraction, is called “an aquifer” [30].

Aquifers can be differentiated on the basis of the hydrodynamic state of groundwater flow and are either confined or unconfined. *Unconfined aquifers* are formed in water-bearing rocks that overlie semipermeable rocks. The part above the saturated zone is called the vadose zone and it enables contact with the atmosphere. The pressure acting on the water table is equal to atmospheric pressure. *Confined aquifers* are formed in water-bearing sediments between overlying and underlying semipermeable rocks. This groundwater is pressurized and the value above the point of contact with overlying rocks is expressed in terms of elevation. Such an aquifer has no direct contact with the atmosphere or surface water bodies, except in zones of recharge and drainage. Depending on its hydrodynamic state of flow, an aquifer can also be semiconfined or leaky, where parts of the aquifer are confined and other parts unconfined.

On the basis of the structural porosity of the rocks in which aquifers are formed, they can be classified as:

- Unconsolidated, found in loose, intergranular porosity sediments, and
- Bedrock, formed in fractured or cavernous (solution-enhanced) rocks, depending on the dominant type of porosity.

Leaky or semiconfined aquifers are found in complex hydrogeological settings, and they represent a combination of the above main types. In most cases, these are karst aquifers. Also in specific hydrogeological settings, several aquifers, although distinctly separate by structure, can be in hydraulic contact and connect stored groundwaters into a single hydrodynamic unit.

Intergranular aquifers are formed in porous rocks of Quaternary or Neogene age. Those richest in water are found in recent alluvial sand and gravel deposits, whose thickness is up to several tens of meters. The main characteristic of alluvial aquifers is a good hydraulic connection with surface water, which is its main source of recharge. Precipitation is another source. There is usually a water table or a slight pressure if the overlying rocks contain semipermeable sediments. Semipermeable overlying sediments are typical of the latter type of intergranular aquifers of Neogene age. The groundwater level is called subartesian if above the roof of the water-bearing rocks, or artesian if above the ground surface. The recharge zone and spread of this type of aquifer do not coincide and can be quite distant from each other.

Fractured aquifers are formed in various igneous, metamorphic (crystalline schist), and solid (non-karstified) rocks. The spread and flow of groundwater vary, depending on age, rock composition, tectonic damage, character, genesis, extent of fracturing, and the like. A fractured aquifer comprises the part above and the part below the local base level of erosion. The part above is within fractured systems found in upper portions of the rock massif. There is a water table and groundwater flow is governed by gravity. Below the base level of erosion, groundwater occurs in large fractures within tectonic fault zones. This part of a fractured aquifer can be in hydraulic contact with other fractured water-bearing rocks. When the aquifer is confined, groundwater flow can be descending or ascending. The recharge zone is generally within the local spread of fracturing and the aquifer is recharged by infiltration of precipitation and/or inflow of surface water or groundwater from neighboring aquifers.

Karst aquifers are formed in solid sedimentary rocks, soluble in water, such as carbonate, sulfate, and chloride sediments. The main feature of these rocks is cavernous (solution-enhanced) porosity. Karst aquifers claim the most favorable recharge conditions, through infiltration of either precipitation or surface water into the cracked and karstified surfaces of karst terrains or geomorphological features. This type of aquifer is characterized by distinct seasonal recharge, considerable groundwater flow velocities, substantial groundwater level fluctuations, and highly unstable karst spring yields. The groundwater level is not continuous and can be either unconfined or confined.

Water abundance of coal deposits

The water content of coal seams is influenced by the coal deposit genesis, depth, presence of one or more overlying, underlying, or adjacent water-bearing rocks, and the number and hydrological and hydrometric characteristics of permanent surface streams.

Coal seams are found in simple, complex, and highly complex hydrogeologic settings [31]. In the case of a simple setting, there are no water-bearing rocks in the coal deposit and the ancillary sediments are semipermeable to impermeable (claystone, compact igneous rocks, and crystalline schists). This group also includes hydrogeologic settings with water-bearing rocks only in the roof of the deposit, made up of sand, gravel, or broken solid rocks (Fig. 7).

Fig. 7 Sandy sediments overlying coal (open-pit mine Field D of the Kolubara Coal Basin (Serbia; photo by D. Polomčić, 2006)

Complex geologic settings of coal deposits are those that feature both underlying and overlying aquifers. The overlying aquifer is (most often) unconfined, formed in sand and gravel, rarely fractured rocks. Recharge is either continuous or seasonal. The underlying aquifer is usually confined, with continuous but difficult recharge, formed in sand or fractured rocks.

Coal deposits in highly complex hydrogeologic settings are layered (Fig. 8). The underlying, overlying, and interbed rocks are largely water-bearing. The overlying aquifer is in alluvial or terrace gravels with an active hydraulic connection with one or more large surface streams. It is usually unconfined. Aquifers between coal seams are found in sands of various grain sizes, they are confined, and their recharge is stable but difficult. The underlying (and adjacent) aquifers are confined and formed in sands and fractured solid or karstified rocks. There is a hydraulic connection between them, and they constitute a single or multiple hydrodynamic and hydrochemical units.

Monitoring of groundwater and surface water

Monitoring of quantitative and qualitative water parameters is required to gain insight into the status of the groundwater and surface water bodies in the area of interest, which is a coal mine in this particular case. Monitoring needs to be established as early as the investigations stage, before a mine is opened, and should continue throughout coal mining.

If there are one or more surface streams near the coal mine, staff gauges need to be installed at certain points to intermittently record water levels. A limnigraph can be used for continuous monitoring of changes (Fig. 9). Apart from surface water levels, insight is needed into water quantity variations at a selected station per unit time. In other words, river discharge needs to be observed. Current meters are used for this purpose, which provide discharge data for various river stages. Such observations are made several times a year, to encompass the entire range of water level fluctuations and construct discharge curves (Fig. 9), which show river stages as a function of discharge. They thus provide insight into the discharge in question for each observed river stage.

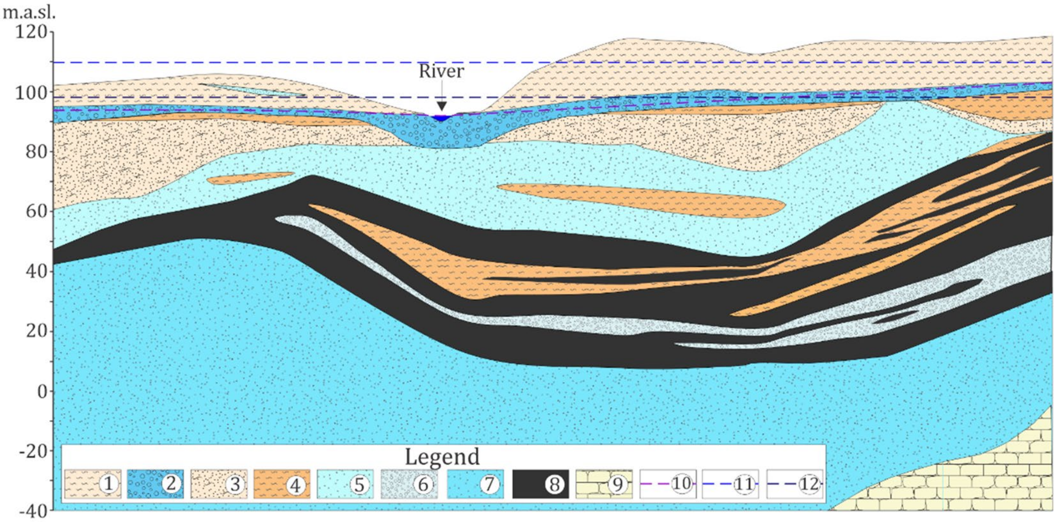


Fig. 8 Highly complex hydrogeologic setting of a coal deposit, with several hydrodynamic units and different groundwater flow conditions. 1 clay; 2 water-bearing gravel; 3 clay, silt, and sand sediments; 4 clay; 5 water-bearing medium-grain sand; 6 water-bearing fine-grain sand; 7 water-bearing fine-grain sand; 8 coal; 9 karstified limestone; 10 groundwater level of the first complex aquifer; 11 groundwater level of the in-between aquifer; 12 groundwater level of the underlying aquifer

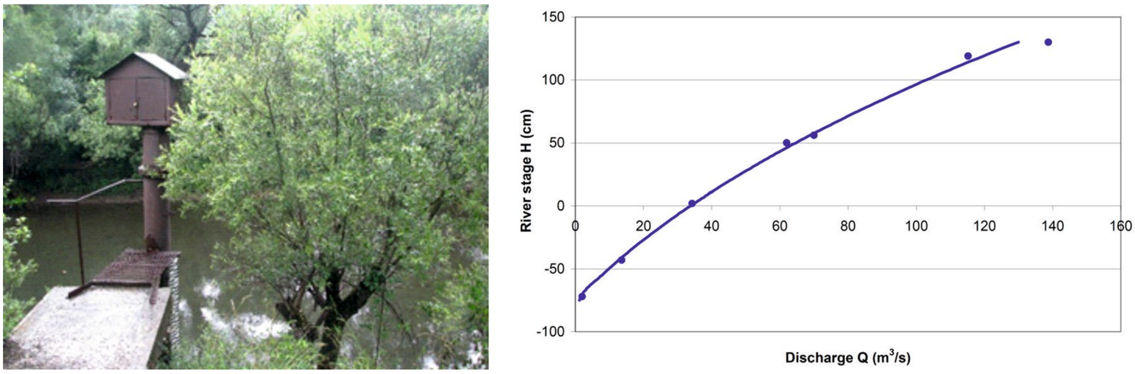


Fig. 9 Limnigraph shelter house and staff gauge (left, photo by V. Ristić Vakanjac, 2006) and discharge curve (right)

In the case of groundwater monitoring, a network of observation wells needs to be designed, the wells drilled, and diver dataloggers installed to continually record groundwater level fluctuations. If the hydrogeologic setting is complex or highly complex, each registered aquifer needs to be monitored separately.

The monitoring data can be used for hydrodynamic and hydrologic modelling. In parallel with quantitative parameters, the qualitative status is monitored by water sampling at certain time intervals and analyses in accredited labs. On the basis of the results, decisions are made whether the quality of groundwater and/or surface water is adequate for human consumption or only industrial use for coal preparation for delivery to end users.

Protection of coal mines against groundwater

A system for the protection against surface water and groundwater is designed depending on the genesis of the coal deposit, depth relative to the land surface, type of mine opening, method of coal mining, complexity of the hydrogeologic framework, and presence of surface streams. Coal mine dewatering in the case of surface water (both meteoric and river water) differs from that of groundwater from overlying rocks, interbeds, underlying rocks, and waste dumps. Drainage systems are built to prevent infiltration of water from surface streams into the overlying water-bearing rocks, including levees, drainage ditches, wells, or impervious screens (fully or partially penetrating). Small surface streams can be realigned, with an impermeable bed or no additional protection. However, in the case of large rivers near coal deposits, the most complete protection system is a combination of an impermeable screen and drainage wells, with levees along the river.

An underground mine or open-pit mine is protected from precipitation by ditches or water collectors.

Groundwater is evacuated by dewatering shafts, vertical wells, horizontal drains, free flow into peripheral ditches, water collectors, or a combination of these methods (Fig. 10).

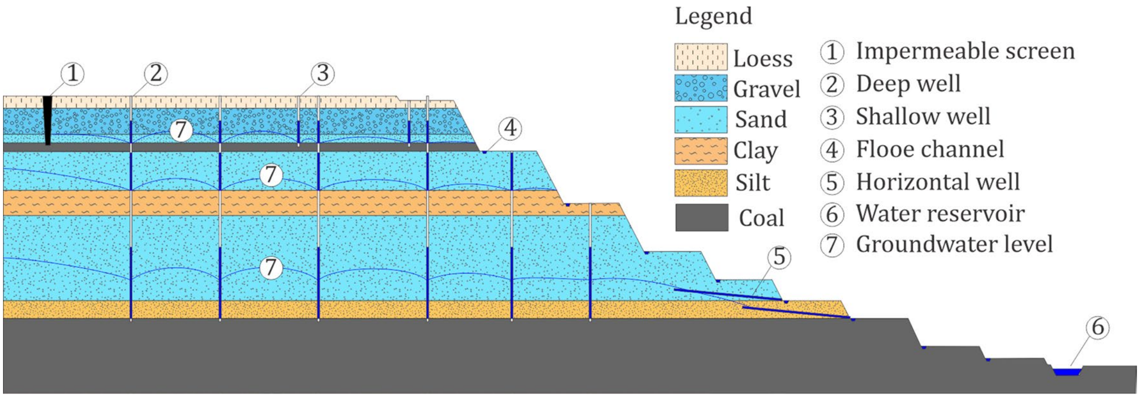


Fig. 10 Water protection system of the open-pit mine Drmno (Serbia)

Coal resources and reserves

The main goal of exploration is to determine the location, quantity, and quality of coal in a particular area. The quantity (resources) and quality of coal are calculated after each stage of drilling and collection of quality data and geophysical, geotechnical, and hydrogeological observations. The first step before calculations is the formation of a database containing all the data collected from the field and laboratory. The database must be well structured to provide information for all calculations using specialized software packages. The second step is loading of drilling, coal quality, and geophysical data into a specific software package and determining the boundaries of coal seam(s). The formation of a block model (Fig. 11), along with the estimation of relevant quality parameters, provides information about coal resources with the quality for each seam. *Coal resource* is a more general term that represents the amount of coal estimated after exploration in a given area. It is the final result of geological exploration of given area, presented in a *geological report*. Coal resources are divided according to the degree of geologic assurance and economic feasibility, as well as the amount of coal which can be technically recovered [2]. *Reserves* are part of the resource and depend on certain limitations such as thickness, depth, quality, and other geological and economic factors that affect mining, and the utilization potential of the coal.

Classification and reporting of coal resources and reserves

Coal resources and reserves are estimated and calculated according to the same standards as all other solid mineral commodities [4, 33]. There are generally two systems/standards for reporting of exploration results, mineral resources, and ore reserves, including the former Soviet approach based on instructions of the Soviet Union State Commission on Reserves, which were well developed and widely used in the former East and Southeast Europe, and other systems widely used by industry and supported by financial institutions, based on measured, indicated, and inferred resources and proven, probable, and possible reserves, later resulting in different CRIRSCO family members [34] and UNFC reporting systems [35].

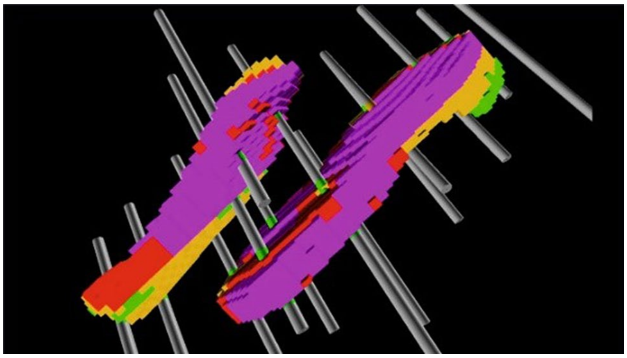


Fig. 11 Block model of coal seams (with permission from the Mickomine Inc [32])

UNFC classification overcomes the issue of multiple non-comparable resource and reserve reporting codes and standards in use across Europe and the world by producing data harmonized for resources and reserves [36]. The United Nations classification has one important advantage compared to bankable reporting standards (JORC, PERC, etc.) as it includes uneconomic and/or undiscovered resources. The main advantages/disadvantages of CRIRSCO and UNFC classification/reporting of reserves are summarized in Table 2.

An economically viable coal deposit depends on the geology of the deposit, coal quality and tonnage, and modifying factors (technical, economic, environmental, societal), as summarized by Pohl [33]. Geological factors, once determined, are constant (do not change over time), while modifying factors may change quite often, either by new methods and technologies, or by changes in legislation, societal demands, or market.

The coal deposit tonnage could be subdivided into resources and reserves (JORC, PERC, etc. [37, 38]). Coal resources include the total volume of coal estimated within the scope of an exploration prospect/permit. Depending on the extent of exploration, coal resources may be inferred, indicated, or measured (as the level of geological knowledge and confidence increases, Fig. 12). Reserves are classified as probable or proven, after consideration of the “modifying factors”, which include mining, processing, metallurgical, economic, marketing, legal, environmental, infrastructural, social, and governmental aspects.

Coal resources and reserves may be estimated by classic hand methods like polygons, cross-sections, and isolines, or by computer software programs, which are required by reporting codes like JORC and PERC. At least for coal, which is still an important internationally traded mineral commodity, we believe that it is quite important that resources and reserves are reported according to the same or similar bankable reporting standard.

Coal utilization

The utilization of coal in industry, especially of bituminous coal, has a history longer than 200 years. Coal was originally used as a source of heat and power in households and industry. Later, in the last quarter of the twentieth century, coal became a key resource for electricity generation

Table 2 Summary of most important advantages/disadvantages of CRIRSCO and UNFC classification/reporting of reserves (slightly modified after [36])

CRIRSCO summary	UNFC summary
Advantages (for regional/national/continental scale reporting)	
Widely used by industry A lot of data is available that adheres to the CRIRSCO template (from industry) Individual codes (PERC, JORC etc.) are clearly defined standards and backed by professional bodies Confidence is given to any reported figures by the need for a "competent person" whose qualifications are clearly defined in the standard The modified McKelvey diagram is very clear way of conveying to non-experts the levels of confidence for different categories	Easy to compare a wide range of commodities using UNFC UNFC can accommodate "uneconomic" and "undiscovered" resources, including early-stage exploration, giving a full picture of known mineral stocks A bridging document has been prepared between CRIRSCO and UNFC, and some national codes to UNFC Although competency to report using the UNFC framework is required, this is not an essential requirement (i.e., the UNFC is not a certifying body). As a result, it is more readily accessed by geological surveys
Disadvantages (for regional/national/continental scale reporting)	
CRIRSCO is not designed for the purpose of national or transnational strategic planning or policy making There is no provision to record anything that is not currently economic. It does not consider known but poorly defined deposits or anything that is not currently worked because of environmental or economic constraints The requirements for a "competent person" are quite demanding and discourage many organizations It is less frequently used for many construction or industrial minerals or by private companies Any work done by governments/geological surveys will most likely not adhere to the CRIRSCO template because it mostly relates to early-stage exploration and pre-competitive research	UNFC is a classification that does not include any rules governing public reporting of estimates. Therefore, it is not accepted for reporting on any stock exchanges and consequently is unlikely to be taken up by large publicly listed companies Many companies do not report data to UNFC and their data will need to be bridged across The three axes approach makes it appear complicated—this can be an issue if trying to communicate with policy makers or encouraging others to adopt it. But 2D representations are also possible Bridging from CRIRSCO to UNFC is not always a one-to-one association but a one-to-many association. More information may, therefore, be required at the deposit level to be sure it is correctly classified

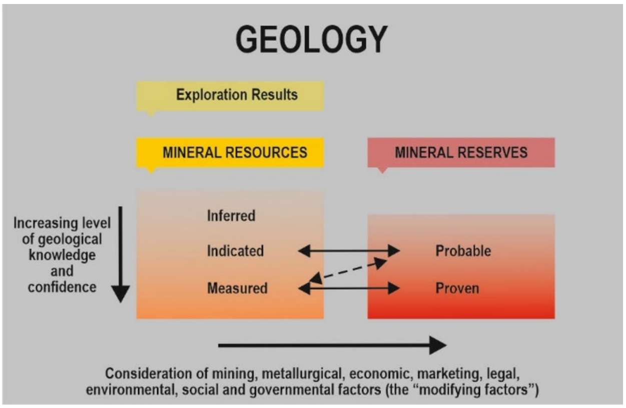


Fig. 12 General relationship between resources and reserves (adapted form source [39])

and steel manufacturing, and thus a major contributor to economic development of most industrialized countries. However, increasing consumption of coal by industry has had a negative impact on the environment [2, 40], such as emissions of CO_2, acid gases, and fine particles, as well as leaching of potentially toxic trace elements from ash and slag. The development of environmental guidelines and enactment of legislation on environmental controls for soil and air pollution led to tremendous improvements in mining techniques, industrial processes, and reductions in greenhouse gas emissions by coal-fired power plants. The damage to the environment and human health caused by the use of coal will be discussed in the next issues of *ChemTexts*.

Today, coal is used for many purposes, such as (1) electric power generation by coal-fired power plants; (2) production of coke used in the steel industry; (3) production of gases and liquids from coal, which can be used as fuel and for petrochemical products; (4) heating of commercial

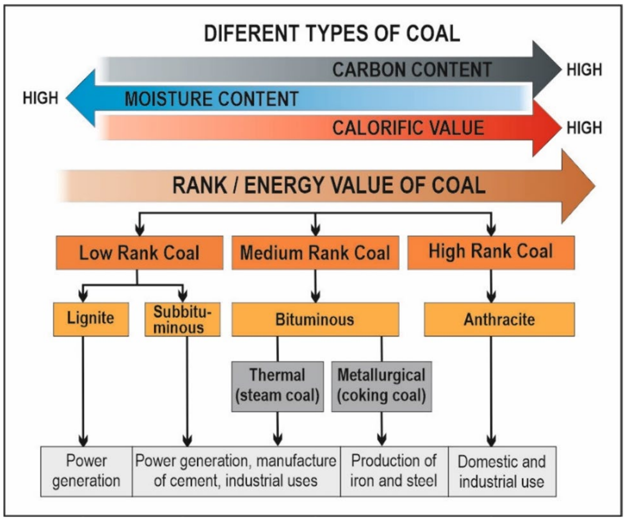


Fig. 13 Types and uses of coal (adapted form source [41, 43])

and residential buildings; and (5) as raw material for the production of carbon electrodes aluminum production, other carbon-based industries, and filters for drinking water production.

Coal utilization depends primarily on the rank and quality [41] (Fig. 13). Brown coal (low rank coal [42]) subdivides into lignite and subbituminous coal, according to rank. Lignite with a high moisture content and a low calorific value and carbon content is mainly used for electricity generation. Subbituminous coal with a higher calorific value and lower moisture content than lignite is used for electricity generation and in industrial processes (cement plants and industrial boilers).

Bituminous coal (medium rank coal [42]) exhibits a higher degree of coalification of organic matter and is used as thermal (steam) and metallurgical (coking) coal. Thermal coal is mostly used for electricity generation, by cement plants and for other industrial purposes, whereas metallurgical coal is primarily used for making coke, which is necessary for the production of iron and steel.

Anthracite (high rank coal [42]), with a very low moisture content and the highest carbon content and calorific value of all coal types, is the most mature coal. In small quantities, anthracite is used as a smokeless fuel in domestic and industrial contexts and for home heating. Figure 13 shows the ranking of different coal types based on their energy values and uses.

Coal combustion

The main use of coal in the past century, at present, and in the near future is combustion to produce steam for electricity generation (Fig. 14). Power generation from coal has gone through various stages of technological development. Since the late 1800s, combustion technologies have undergone major changes [8] related to new construction materials, system designs, and advances in steam production. Today, modern boilers are designed to burn coal of different grades (lignite to anthracite) and qualities. Increasingly stringent environmental controls and the implementation of new standards have led to new investments in research and development of more efficient clean coal technologies and better compliance with standards.

The principle of electricity generation from coal is similar to other thermal power stations. Coal is burned in a boiler, heating water to produce steam. The steam spins a turbine to produce electricity. Several systems can be used to burn coal, including [44] (a) fixed bed, (b) fluidized bed, and (c) entrained bed.

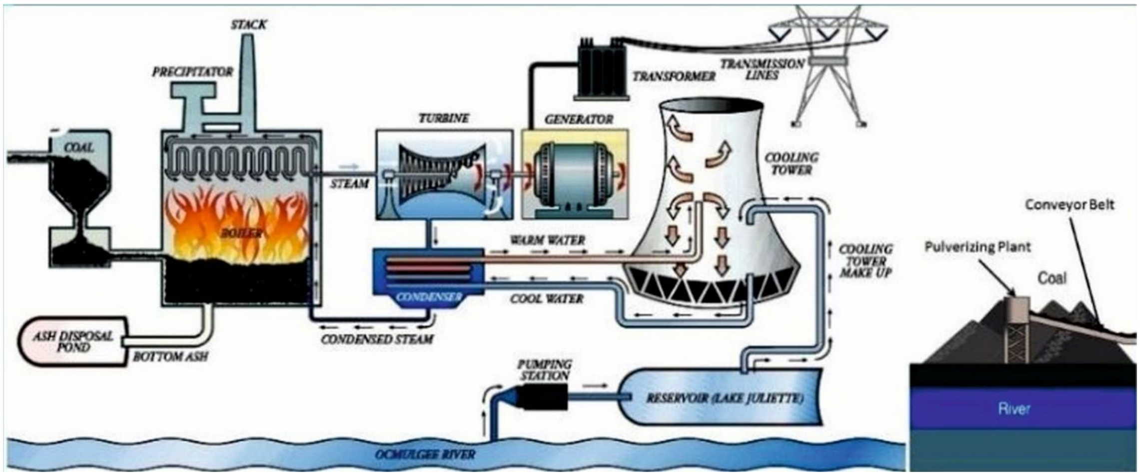


Fig. 14 Generalized diagram of electricity generation [53]

Fixed bed systems are used in different types of industrial, small-scale stoker boilers. In this system, coal particles (diameter < 30 mm) are burned while moving in a transport-type combustion chamber. *Fluidized bed combustion* became very popular at the end of the twentieth century because it supports combustion of low-quality coal and provides better heat transfer in the bed. Crushed coal grains (diameter < 10 mm) are air blown into the fluidized bed, where they burn at temperatures from 800 to 900 °C in the fluidized boiler. During combustion, limestone may be added to the bed as a sorbent for sulfur oxide (SO_x), including SO_2 (desulfurization process). Also, lower combustion temperatures in the boiler help reduce the nitrogen oxides (NO_x) emitted from the system. An *entrained bed* combustion system is used for large-scale power generation, where injected pulverized (powdered, diameter < 70 µm) coal burns for several seconds at flame temperatures of 1400–1500 °C.

Apart from steam for power generation, coal combustion produces waste material—coal combustion residuals or coal combustion by-products. Coal combustion residuals [45, 46] are composed of fine particles of burnt coal (ash), which are ejected from the boiler along with flue gases. There are three types of ash: (a) bottom ash, (b) boiler slag, and (c) fly ash.

Bottom ash is composed of coarse and relatively heavy particles that fall into the boiler's combustion chamber after burning in dry-bottom boilers. It contains melted minerals left over from burning, comprising mostly silica, alumina, iron, calcium, and magnesium, with low concentrations of other elements. The proportions of major, minor, and trace elements depend on the mineral composition of coal and combustion conditions.

Boiler slag is similar to bottom ash but is a by-product of coal combustion in wet-bottom boilers. Fused ash is extinguished with water to form a black, solid, and glassy waste product called slag.

Fly ash, flue ash, coal ash, or pulverized fuel ash is a coal combustion by-product composed of burnt coal particles (size 0.5–300 µm) captured by filters. In modern power plants, fly ash is picked up by electrostatic precipitators or other types of filtration equipment before the flue gases reach the stacks. Fly ash is mostly composed of silica, alumina, iron, and calcium, while magnesium, sodium, potassium, and phosphorus occur in minor amounts. The following trace elements are found in fly ash: As, Be, B, Cd, Cr, Co, Ga, Pb, Mn, Hg, Mo, Se, Sc, Tl, and V, as well as dioxins, polycyclic aromatic hydrocarbons (PAH), and other carbon compounds. Fly ash had previously been released into the atmosphere, but current air pollution standards require it to be captured by pollution control equipment.

Flue gas is the gas released into the atmosphere during combustion of fossil fuels in power plants. It is composed mostly of nitrogen, carbon dioxide, and water vapor. Flue-gas desulfurization (FGD) is a set of technological methods used to remove sulfur dioxide (SO_2) and oxides from flue gases in coal power plants. The most common residues of these processes are "synthetic" gypsum and spray dryer absorbents.

The mineral and chemical composition of coal combustion by-products largely depends on the coal rank, type, and grade [47], as well as combustion conditions. The largest portion of bottom ash, fly ash, and flue-gas desulfurization products from coal-fired power plants are stored in specially designed places, in landfills, ash ponds, and waste dumps, which may cause environmental problems. According to the American Coal Ash Association [48], from 2000 to 2018 the USA annually produced 100 to 130 Mt of combustion waste from coal-fired power plants. This amount decreased to approximately 78 Mt between 2019 and 2021. The majority of these materials are disposed of in ash ponds and only 10–15% are recycled. Progress in sustainable management of coal combustion by-products has provided many new and innovative recycling solutions and efficient reuse. Coal combustion products, bottom ash, fly ash, and FGD are effectively used in the construction and ceramic industries, for wastewater remediation, soil amelioration, catalysis, and recovery of valuable metals (REEs), as a precursor for material synthesis, and the like. The advantages and limitations of the use of coal combustion by-products are discussed in many published papers and books [16, 44, 49–52]. Figure 14 is a generalized schematic diagram of electricity generation from coal.

Coal carbonization

Coal carbonization, or coking, is a process of thermal decomposition of coking coal (metallurgical coal) at temperatures from 1000 to 1200 °C in a coke oven battery [5, 8] (Fig. 15) without air, whereby coke (carbonaceous

Fig. 15 A battery of coke ovens [54]

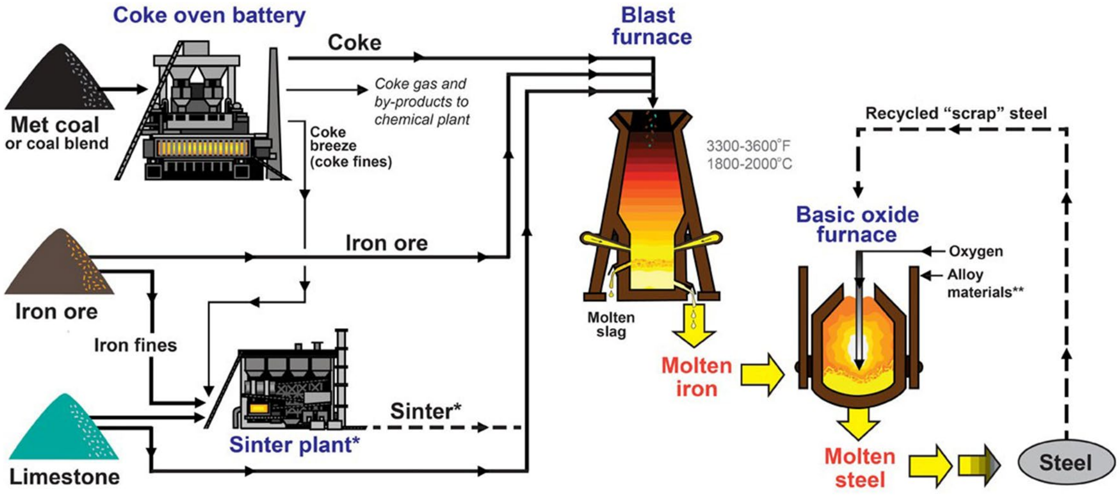


Fig. 16 Generalized diagram of steel production (with permission from the Kentucky Geological Survey and University of Kentucky [62])

residue), gases (coke oven gas), tar, and benzene are produced. The coke, with a mixture of iron ore and limestone, is delivered to a blast furnace to make molten iron, which is then treated and heated further in a basic oxide furnace to make steel (Fig. 16).

Coke ovens are typically 6 m high, 15 m deep, and half a meter wide. They are arranged in batteries of up to 100 ovens stacked together. About 15 to 30 t of coking coal, usually a blend of several different coals, is heated and converted into coke in about 18 h. The volatile matter from coal leaves in the form of gases and tars, collected for use as by-product chemicals.

Only small amounts of coal can be used for coking. Coking coal must have several qualitative characteristics. A good coking coal is of bituminous rank (mostly in low- to medium-volatile stages), with a high vitrinite concentration and a low ash ($<7\%$), sulfur ($<1\%$), volatile matter (10–40%), phosphorus, chlorine, and alkali content, along with good caking and coking properties. A number of tests can be used to determine the caking and coking properties of coal [2, 6], such as the free swelling index and agglutinating value, the Gray-King assay, and the Audibert–Arnu dilatometer. The relative content of "reactive" (vitrinite and liptinite macerals) and "inert" components (inertinite macerals and mineral matter) is an integral part of the (microscopic) examination of coking coal before the carbonization process.

During the carbonization process, coking coal softens, liquefies, and then solidifies into a compact porous material—coke. Coke is predominantly composed of carbon with a low content of thermally altered remains of different minerals present in the original coal. Nearly 90% of coke is produced from blends of coking coals [55]. Carbonization of 1.25–1.65 t of blend coking coals yields 1 t of coke and generates about 300–360 m^3 of coke oven gas (6–8 GJ/t coke [56]). Coke oven gas is a valuable by-product of coal carbonization, and it originates from volatile matter in coal [57]. It is a mixture of different gases, such as CO, CO_2, CH_4, H_2, N_2, C_2H_2, C_2H_4, H_2S, and HNO_3. A portion of them can be reused [56, 58–60]. Effective recovery and utilization of coke oven gases for valuable fuel will be a future challenge. Steel industry is the base of modern civilization, and according to world trends emits huge amounts of CO_2, which represents about 8% of the total global emissions [61]. Decarbonization of the primary production of iron and steel with reduce emission of CO_2 is the focus of research. Hydrogen-based direct reduction and hydrogen plasma smelting reduction (HyPSR) according to the latest research [61] are the most promising candidates for a successful replacement of coke in the ironmaking industry.

Coal gasification

Coal gasification is the fundamental technology for converting coal or any carbon-containing material to synthetic natural gas (SNG) under high temperature and pressure [5, 10]. Carbon from pulverized coal reacts with steam (from water, Fig. 17) and oxygen at a pressure greater than 30 bar and temperatures of about 1500 K (approx. 1227 °C) to produce raw synthesis gas and minor by-products [63]. Raw synthesis gas or syngas is a mixture of carbon monoxide (CO) and hydrogen (H_2). The by-products are composed of hydrogen sulfide (H_2S), carbon dioxide (CO_2), and slag (originating from minerals in coal). They are removed to produce clean syngas, which can be used as a fuel (to generate electricity),

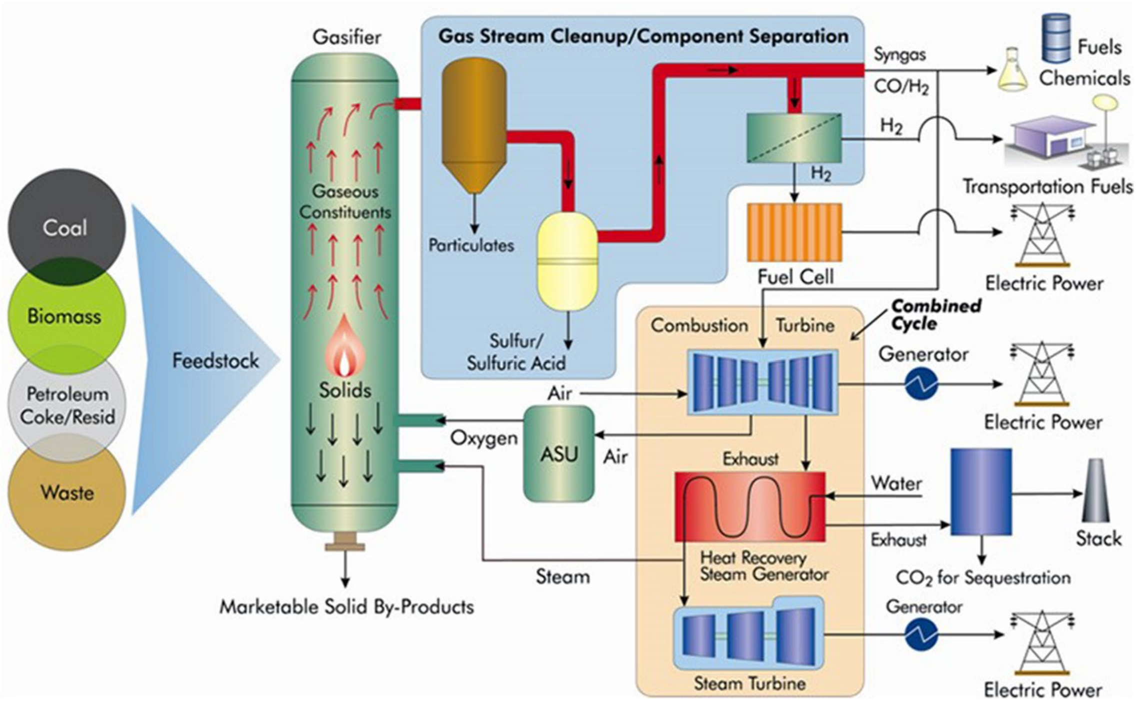


Fig. 17 Generalized diagram of the gasification process [65]

in the petrochemical and refining industries, and for hydrogen production.

In the past, coal was one of the most important natural resources for industrialization. The first coal gasifier was used in 1780 [64]. In the early 1800s, coal gasification was the leading energy source for industry and provided heating and lighting in Europe and America. Unfortunately, the benefits were accompanied by negative effects, especially the discharge of poisonous gases (hydrogen sulfide, hydrogen cyanide, and ammonia). These components were soon separated and cleaned. In the first stages of industrialization there were two main types of coal gasifiers—cyclic gas generators and gas producers. Today, 12 major types of gasifiers are in operation [64].

The idea of underground gasification of coal was presented in the late 1800s, but the first tests were not conducted until the 1930s in the former USSR [2]. Since the 1970s, the process has been improved through extensive testing in laboratories and in the field in the USA and Europe. Low prices of crude oil and natural gas in the 1980s and 1990s stopped the commercialization of underground coal gasification. Recent research at different depths of coal seams (250 m, 500 m, 1000 m) has provided positive results.

Underground coal gasification (UCG) is an in situ process of gasification in deep non-mined coal seams, based on the injection of steam and oxidants [66] through injection wells (Fig. 18). The produced synthesis gas is transported to the surface through production wells. Synthesis gas can be used in the production of electricity, fuel, and chemicals. Injection wells are used to deliver air, oxygen, and steam to coal seams under pressure and to ignite and accelerate the underground combustion process. Production wells are separate and used to bring the gas product to the surface. Underground combustion at temperatures of 700–900 °C, or even as high as 1500 °C [67], decomposes coal and generates gases. In this process, carbon dioxide (CO_2), hydrogen (H_2), and carbon monoxide (CO) are generated in large quantities, instead of methane (CH_4) and hydrogen sulfide (H_2S), which are produced only in small quantities.

The rank, maceral composition, and cleat system of a coal seam have a significant effect on natural permeability to transport the gas. Breaking up of the coal under high pressure, hydro-fracturing, electric linkage, and reverse combustion may be used to increase the natural permeability of coal, but with varying success. According to research conducted in the past several decades, coals of different rank, from lignite to bituminous, can be gasified successfully. However, other important criteria apply, such as (a) coal seam depth of 100–1400 m; (b) coal seam thickness greater than 5 m; (c) ash content less than 60%; (d) minimal discontinuities; and (e) isolation from valued aquifers.

Underground coal gasification, like most technological processes, has advantages over surface gasification, including [67]: (a) reduced costs of operating surface mines, land damage, mine safety measures, transportation and storage of coal, capital expenditure for surface

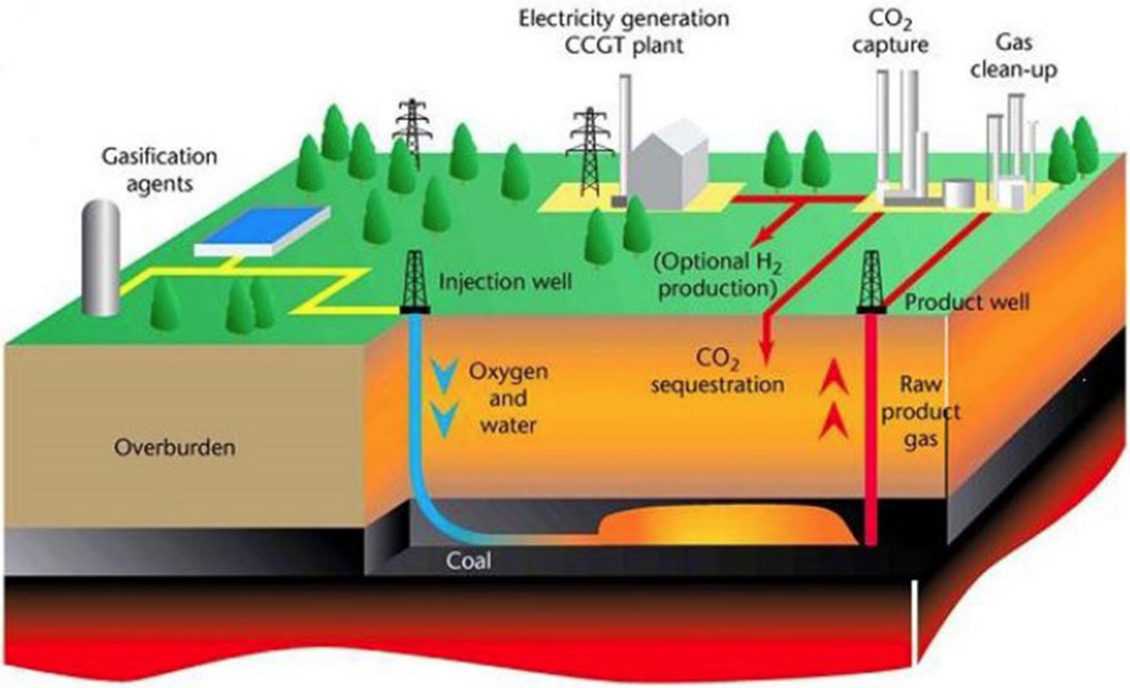


Fig. 18 Generalized diagram of underground coal gasification [68]

gasification facilities (gasifier), and ash disposal on the surface; (b) utilization of non-mineable coals (very thin coal seams, coal of low quality, too deep for mining—too expensive or technically not feasible); (c) low emissions of SO_x, NO_x, and other gasses and pollutants; (d) part of the well infrastructure for UCG can be used later for CO_2 sequestration operations; (e) using UCG makes it possible to extract more than 80% of energy, whereas the coal seam gas technology can extract only 3–5% of the energy as methane.

The limitations of commercial USG include the following [2]: (a) aquifer contamination and ground subsidence; (b) UCG may be technically possible, but geological and hydrogeological factors might raise environmental risks to unacceptable levels; (c) the process can be controlled indirectly through temperature measurement and the production of gases and their quality; (d) the flow rate and heating value of the product gas will vary over time; (e) the economic profitability of a UCG power plant is debatable and depends on market supply and demand. Geological factors, due to the generation of earthquakes, could damage boreholes and surface installations and might raise pollution of environment [68].

Both surface and underground coal gasification have a future, as the most environmentally friendly process [66, 69], compared to other coal technologies. The capture and sequestration of CO_2 are the main benefits of these processes, while reduced sulfur and mercury emissions, and no ash and tar discharges, are additional benefits. Integrated gasification combined cycle (IGCC) based power plants are more expensive than conventional coal-fired power plants, but they are more efficient and environmentally friendly because of carbon capture and environmental controls [66].

Coal liquefaction

Coal liquefaction is a technological process of coal conversion into liquid hydrocarbons [5, 9] (liquid fuels and petrochemicals, Fig. 19) under high temperature (400–500 °C) and high pressure (6.9–71.0 MPa) in the presence of hydrogen gas with or without a catalyst, to produce fuel and improve efficiency. Beginning in Germany, the process has been commercially developed since the 1920s [70]. In Germany, seven hydrogenation plants were operating in 1939 and 12 in 1944. Six of them directly hydrogenated brown and bituminous coal, and the other six hydrogenated tar derived from coke distillation plants to produce high-quality motor fuels, chemicals, and gas. Research and development of coal liquefaction processes are ongoing. Synthetic liquid fuel production from coal is still limited because of high cost. Various technological processes of coal liquefaction have been developed to date, which differ in liquid yield and solid products [2]. These technologies include (a) direct liquefaction by hydrogenation, (b) indirect liquefaction by Fischer–Tropsch (FT) synthesis, and (c) partial removal of the carbon content from coal by pyrolysis.

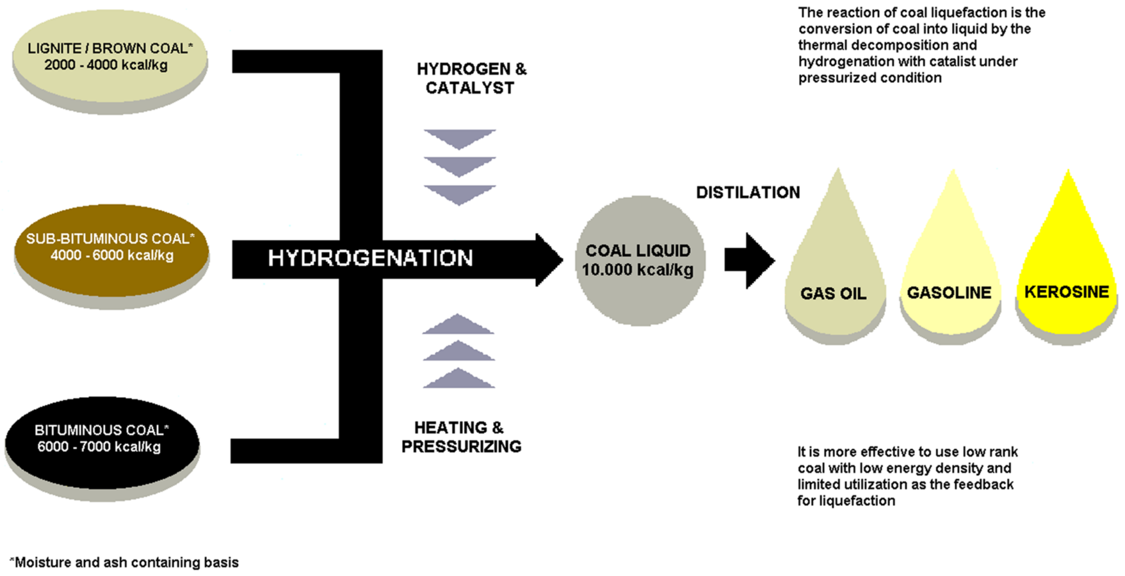


Fig. 19 Coal liquefaction concept [73]

In direct liquefaction, pulverized coal first reacts with a catalyst under high pressure and temperature. Hydrogen is added as a thermally stable solvent to produce raw liquid fuel. Raw liquid fuel is than refined (filtered and distilled) to separate the solvent from the coal extract.

Indirect FT synthesis was developed in the 1920s in Germany and it represents basic production of oil from coal in Sasolburg, South Africa, known as SASOL, which has become synonymous with the process. FT synthesis comprises two steps. The first step is gasification of coal in a Lurgi gasifier to produce synthesis gases (syngases), carbon monoxide, hydrogen, and methane. Treated methane is synthesized in a Kellog reactor, while carbon monoxide and hydrogen are used in the second step. The second step is based on reactions of a synthesis gas (CO, H_2) with a catalyst in the FT process. A range of hydrocarbon fuels, such as gasoline, diesel, and methanol, result from cracking in this process.

The third process, pyrolysis, is extremely rapid heating of pulverized coal in a vacuum, known as flash pyrolysis. During pyrolysis, macerals reacting in the plastic stage become soft and decompose into gas, char, and tarry liquids. Tar is then hydrogenated to produce heavy or light oil.

Extensive research over many decades has shown that coal quality requirements for liquefaction depend on the method, chemical composition, petrologic composition, and rank. Coal suitable for liquefaction should fulfill several qualitative criteria [1], including (a) vitrinite reflectance $<0.8\%$, (b) H/C atomic ratio $>0.75\%$, (c) vitrinite + liptinite $>60\%$, (d) volatile matter (dry ash free, daf) $>35\%$, and (e) low content of heteroatoms.

Lignite, subbituminous coals, and highly volatile bituminous coals with an appropriate content of “reactive macerals” (vitrinite + liptinite) are suitable for liquefaction. Liptinite macerals are highly reactive over a wide range of rank and under most liquefaction conditions [70], compared to vitrinite macerals which first increase and then decrease with increasing rank. Inertinite exhibits a different degree of reactivity. Macerals with a higher reflectance (fusinite) should be inert during liquefaction, while those of lower reflectance (semifusinite) may be semi-inert and lead to increasing oil yields [71]. The inertinite-rich, highly volatile bituminous coal with a high ash content from South Africa is used effectively for FT synthesis in SASOL plants [2]. Inorganic impurities in coal consist of different minerals of various chemical compositions and have a different effect on the coal liquefaction process. Generally, a high ash content can cause problems with solid and liquid separation, and can deactivate any catalyst, while some minerals could have a catalytic effect. Pyrite, for example, has favorable catalytic properties [1]. Experimental evidence has shown that the addition of pyrite, dimethyl disulfide, elemental sulfur, and H_2S in the liquefaction process leads to an increase in total conversion product yields, while the addition of other Fe minerals, such as pyrrhotite, iron oxide, iron sulfate, and the like may decrease conversion or have a minimal effect [70].

Extensive studies of the conversion of low-rank brown coals into liquid products using the direct catalytic hydrogenation process showed a high degree of conversion [72] and suggest better utilization of low-rank coals in the future.

Today, the main products of the FT process in a SASOL plant are diesel, petrol (gasoline), naphtha, kerosene (jet fuel), liquid petroleum gas (LPG), olefins, alcohols, polymers, solvents, surfactants (detergent alcohols and oil-field chemicals), co-monomers, ammonia, methanol, various phenolics, sulfur, illuminating paraffin, bitumen, acrylates, and fuel oil [11]. These are used to manufacture a variety of everyday products worldwide and benefit the lives of millions of people. They include hot-melt adhesives, car products, microchip coatings, printing ink, household and industrial paints, mobile phones, circuit boards, transport fuels, compact discs, medical lasers, sunscreens, perfumes, and plastic bottles. Also, SASOL produces an extensive range of fertilizers and explosives and is a world leader in its low-density ammonium nitrate technology.

Carbon materials derived from coal

Since 1991, when Pang and associates [74] were the first to report the production of fullerenes from Australian coke, there have been many studies on the transformation of coal into various classes of carbon materials. Coal is a complex mixture of substances which consists of three-dimensionally cross-linked aromatic and hydroaromatic compounds connected by short aliphatic and ether linkages [9, 75]. Compared to graphite, coal is a low-cost natural resource and a very promising source for carbon nanomaterials. The development of coal-based carbon materials (CCMs) in the past few decades has resulted in the production of various functional carbon materials from coal and its derivatives, such as porous carbons, fullerenes, carbon nanotubes (CNTs), carbon spheres, carbon fibers, graphene, and carbon quantum dots (CQDs) [76, 77] (Fig. 20).

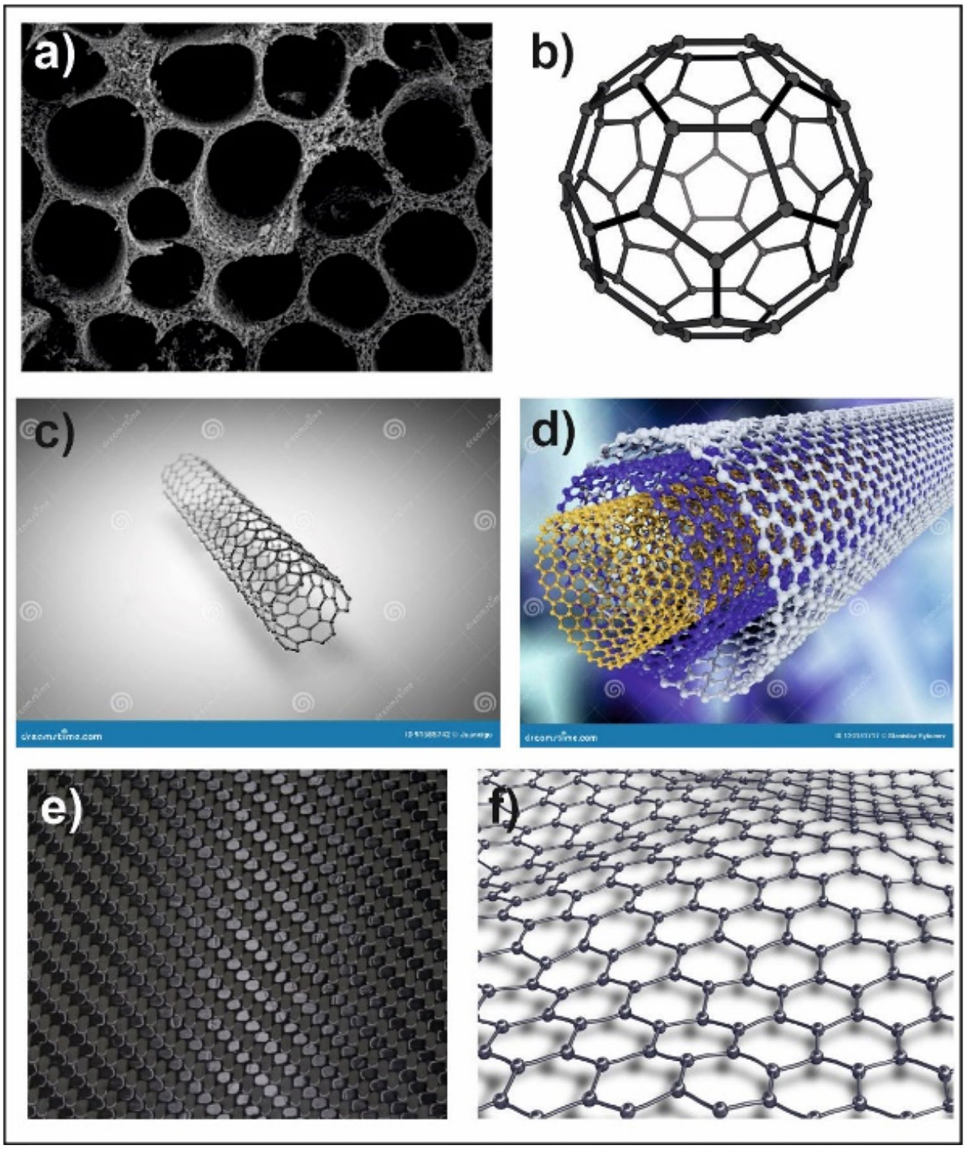


Fig. 20 Various types of carbon materials derived from coal; **a** porous carbons (with permission from The Royal Society of Victoria [84]), **b** fullerene [85], **c** single-walled carbon nanotubes (with permission from Dreamstime ID91585742 ©Juanxigu [86]), **d** multiple-walled carbon nanotubes (with permission from the Dreamstime ID120181717 ©Stanislav Rykunov [87]), **e** carbon fiber (with permission from the Carbon Fiber Gear [88]), **f** graphene [89]

The most important *porous carbons* are activated carbons which are widely used in wastewater treatment, gas separation, heterogeneous catalysis, energy storage, etc. [77]. Coal (bituminous coal, anthracite) is the main precursor of activated carbons. Coal tar, coal tar pitch, and asphaltene can be used as sources for activated carbons.

Fullerenes are allotropes of carbon, whose carbon atoms are connected by single and double bonds to form a fully or partially closed mesh, with fused rings of five to seven atoms. The molecule may be a hollow sphere, ellipsoid, tube, or have many other shapes and sizes. Fullerenes are reactive and can combine with a large number of organic or inorganic substances to form new compounds with given physical and chemical properties [78]. Many studies have been undertaken to examine the preparation of fullerenes from different types of coal [77]. Fullerenes have been the subject of extensive research, especially in materials science, electronics, and nanotechnology.

Carbon nanotubes (CNTs) are tubes made of carbon in the nanoscale diameter range. They are allotropes of carbon, which can be divided into two categories [77]: single-walled carbon nanotubes (SWCNTs) and multiple-walled carbon nanotubes (MWCNTs). Several methods have been developed over the past 30 years to synthesize CNTs from coal and coal-based derivatives, such as arc discharge, laser ablation, chemical vapor deposition (CVD), and the like. Coal has shown potential for large-scale production of CNTs, as a cheap carbon source [79].

Carbon spheres have been the subject of a large number of investigations in the past several decades. Their properties, such as light weight, high specific surface area, high chemical inertness, and high thermal stability [77, 80] make them attractive for utilization and research.

Carbon fiber filament is a type of 1D carbon material synthesized from coal and coal tar pitch by different methods. It is used to improve the properties of base materials [77].

High thermal conductivity, high tensile modulus, and efficient charge carrier mobility of *graphene* [77] make it a very attractive material. Graphene is a thin carbon material consisting of a single layer of atoms arranged in a hexagonal lattice nanostructure [81], made from coal with abundant aromatic structural units (bituminous coal, anthracite), graphite, and coke applying several techniques [76]. In addition, graphene oxide has been isolated from low-rank coal [82]. Low-cost preparation of coal-based graphene will be a challenge in the future.

Carbon dots, also known as carbon nanodots, were first discovered when fluorescent materials inside carbon nanotubes were examined [83]. Their unique properties, as well as high photochemical stability, good biocompatibility, and low environmental impact, make them a valuable and attractive class of fluorescent carbon nanomaterials, derived from coal and its derivatives.

Alternative uses of coal through various functional carbon materials, including the remediation of environmental pollution and solar energy conversion or storage, make them a valuable resource for the future.

The direct carbon fuel cell (DCFC) is a type of high temperature fuel cell that converts chemical energy of solid carbon-rich material (coal or bio-mass) into electricity with the release of carbon dioxide as a by-product. Recent studies and developments in DCFC performance showed higher efficiency then conventional steam power plants [90] and clean and efficient carbon utilization methods. The technology is at an early stage of development and requires many complex challenges. DCFCs offer the possibility to generate "clean" electricity [91] and their future development may provide a new electricity source for several decades.

Global coal production and its usage in future will depend of many factors and the role of coal in future global energy systems. From an economic point of view, coal is one of the world's most important primary sources of energy, and will be in the future. On the other hand, the usage of coal has a negative environmental impact and could be "dangerous" compared to other energy sources and should be avoided. Long-term forecasts predict a global peak of coal production until 2050 [92], and will depend on recoverable reserves, primary electricity demand, and the possibilities of faster replacement of coal with renewable energy sources. Also, future coal utilization has been limited by political decisions. Coal in the next several decades will have a significant share in energy production at the global level. Comprehensive research shows several factors of increasing coal production after the COVID-19 pandemic and failure in global green recovery [93]. The instability of energy prices caused by the COVID-19 pandemic, climate change, and geopolitical crises are the primary factors affecting the increased production of coal in most countries. In addition, the expected economic growth in countries with lots of coal reserves, their reliance on the coal economy, political influence of the coal sector, the revival of geopolitics, and concerns about energy security may affect the increase in coal production in the long term. Also, the influence of geopolitics on the energy transition in the coming decades can not be excluded. Such predictions illustrate the great challenges facing the global green recovery in the future.

Conclusions

Coal exploration is a set of activities aimed at discovering coal-bearing sediments and coal deposits that can be exploited profitably and utilized in an environmentally acceptable manner in the future. The exploration process implies the use of a variety of geological techniques to determine the location and quality, assess the extent of resources, and identify geological factors that will facilitate or constrain mine planning and future exploitation.

Coal exploration includes field activities, laboratory work, and the estimation of resources and reserves. Field investigations of coal seams and coal-bearing sediments are the first step that provides significant information for planning of the drilling program. Drilling is a base method used in coal exploration, which provides information about the coal seam thickness, coal quality, and the lithology of the sediments and associated rocks.

Geophysical investigations of coal are carried out to help define the geologic framework, locate and outline coal seams, characterize coal deposits, and address problems of coal mine stability and safety. Geophysical methods are often divided into potential methods that study natural fields related to the planet Earth (force fields) and methods based on physical interactions (induced physical fields). Potential methods analyze and interpret gravity and geomagnetic field variations. The latter group detects artificially produced signals transmitted through the Earth's crust, which are modified depending on the physical properties of the rock mass through which they pass.

Geotechnical investigations provide information on the physical properties of soil, coal seams, and all lithological types associated with coal-bearing sequences. These data are necessary for designing future open-pit or underground mining. Geotechnical investigations include surface and subsurface exploration of an area, along with sampling and laboratory testing.

The water content of coal seams is influenced by the coal rank, depth, presence of one or more overlying, underlying, or adjacent water-bearing rocks, and the number and hydrological and hydrometric characteristics of permanent surface streams. Coal seams are found in both simple and highly complex hydrogeologic settings. Monitoring of quantitative and qualitative water parameters of the deposit and mine is required. Monitoring needs to be established in the exploration stage and should continue throughout coal mining.

The main goal of exploration is to determine the location, estimate the quantity (resources), and define the quality of coal in the studied area. Calculation of resources is undertaken after each exploration stage. Coal resources and reserves are estimated according to the same standards as all other solid mineral commodities and reported on the basis of national and international standards (JORC, PERC, etc.). Coal resources include the total volume of coal estimated under an exploration prospect/permit. Depending on the exploration level, coal resources may be inferred, indicated, or measured. The reserves are classified as probable or proven, after considering "modifying factors", which include mining, processing, metallurgical, economic, marketing, legal, environmental, infrastructural, social, and governmental aspects.

Coal utilization depends primarily on the coal rank and quality. Coal is used for electric power generation in coal-fired thermal power plants, heating of commercial and residential buildings, and the production of coke used in the steel industry, as well as gaseous and liquid products which can be used as fuel, in the petrochemical industry, and as a raw material for the production of coal-based carbon materials. Coal by-products are used effectively in the construction and ceramic industries, for wastewater treatment, soil remediation, catalysis and recovery of valuable metals (REEs), as a precursor for material synthesis, and so on.

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Data availability The authors confirm that all relevant data are included in the article.

Declarations

Conflict of interest The authors declare no competing interests.

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