Chapter 7

Coal

Chapter Objectives:

1. List and describe 4 types of coal.
2. Discuss the environmental impact of coal production.
3. Describe measures to burn coal more cleanly.
4. Describe coal gasification and coal liquefaction techniques.
5. Discuss the current state of coal reserves and methods to extract them.

History

Coal has been a source of energy for almost as long as Homo sapiens have inhabited the planet. The earliest record for its use dates back more than 3000 years to China where it may have been used to smelt copper[1]. In areas where coal seams intersected the surface, coal was a ready supply of energy just waiting to be exploited. It did have some drawbacks, though. Most of the coal near the surface burns dirty, requiring some form of chimney if it is to be used indoors. It is also heavy to transport, limiting its use to regions near the source. Because of this, the use of coal through history was fairly sporadic. There is evidence for its use in Iron Age Britain, as well as in Rome near the beginning of the Common Era[2]. Its earliest use in the U.S. was in the 1300's by Hopi Indians in the desert Southwest for cooking and pottery-making[3].

Fig. 1: illustration of Chinese coal miners from the Tiangong Kaiwu encyclopedia

With improvements in mining, transportation, and ventilation in Medieval Europe, coal use gained in popularity. However, it was not until the beginning of the Industrial Revolution that coal use really took off. Large-scale manufacturing and transportation required tremendous amounts of energy, the likes of which wood could never supply without very quickly denuding every forest in Europe. Coal also had the advantage of being able to be used to make coke, which is used to manufacture steel. The invention of the coal-powered steam engine by James Watt furthered the use of coal. It lead to the train and the creation of the steam-powered boat, which made possible the quick and reliable transport of the manufacturing plants goods to faraway locations.

The timing of this revolution could not have been better for the U.S. from an economic standpoint. Coal had been discovered in the Colonies in the late 1600's, and the first commercial mines began operation in the 1740's. The plentiful supplies of this in places that were then Virginia and Pennsylvania helped the young country grow into an industrial powerhouse.

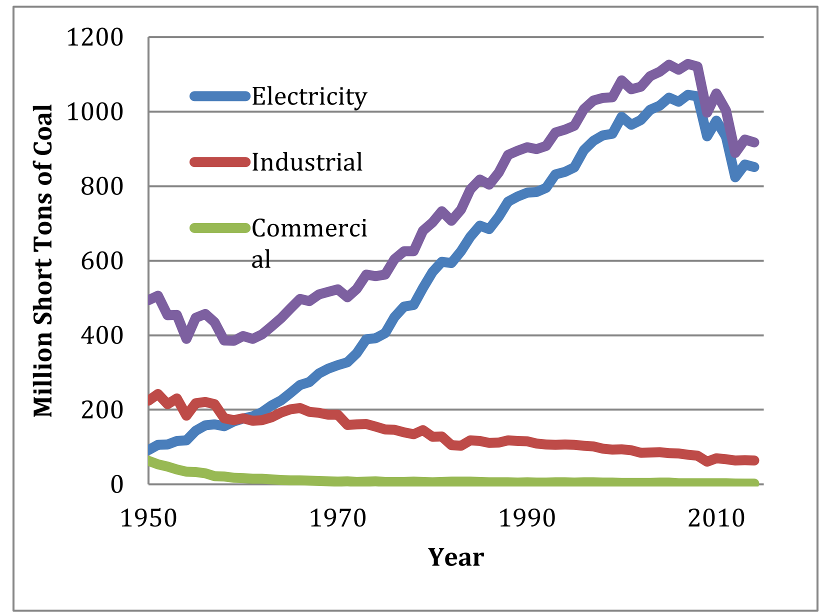


Fig. 2: Coal consumed for electricity[6]

Usage

Today, coal is still heavily involved in many applications in the U.S., but its use has been declining. The reason for this is that the lower levels of cost and environmental damage by some other sources are making them more attractive. For a very long time, we have had a large and readily-available supply of coal in the U.S. Its cost to produce and use has been very cheap, as long as the cost of repairing the damage done by mining and using it are not considered. We currently use over 1 billion short tons of coal per year in the U.S. Given that we have an estimated recoverable reserve of over 270 billion short tons of coal in our country alone[4], we should be able to supply our own needs for a long time.

Of the coal that we are using, the overwhelming majority of it (93%) goes toward the generation of electricity for sale to the public. It currently accounts for about 39% of the electricity generated in the U.S.[5,6] This is much less than the 50% of the share that coal had just years ago. As you can see from Figure 2, the amount of electricity generated from coal has been decreasing for several years now. This has a lot to do with the low cost (both economic and environmental) and the greater efficiency of electricity created from natural gas. As of the summer of 2015, natural gas has surpassed coal as the largest supplier of electricity[7]. This trend is likely to continue if natural gas remains cheap and plentiful.

Coal does get used for other purposes, although some of these uses get mixed with generating electricity. About 4.7% of the coal used in the U.S. goes toward other industrial uses, which can include those that create electricity for use on site or for combined heat-power generation. Another 0.2% is designated as residential/commercial use, which is mostly used for heat, but can be used for generating electricity at universities and hospitals. The remaining 2.3% of the coal consumed in the U.S. goes toward making coke, which is used in the refining of metal ores.

From where does all of this coal come? Since we have such a large supply, most of it comes from the U.S. We do import a small amount of coal (about 16 million short tons) from all over the world, but we export far more than this (about 40 million short tons). This means that we are a net exporter of coal, which is far different than the situation with oil.

TOP COAL-PRODUCING STATES (2014) (THOUSAND SHORT	
STATE	**AMOUNT**
Wyoming	395,665
West Virginia	112,187
Kentucky	77,335
Pennsylvania	60,910
Illinois	57,969

When we think of locations for mining coal in the U.S., most people think of Kentucky or West Virginia. However, the largest portion of our coal comes from Wyoming. From just 18 mines, this state produces almost 400 million short tons of coal a year, which is over one third of our total usage. By comparison, West Virginia and Kentucky (which are our second and third largest producers) accounted for only 112 and 77 million short tons in 2014, respectively, from 443 mines in total. The combined output from these three states is about two thirds of our total output[8].

Creation

The story of how coal is created is very similar to that for oil. However, it does vary in several key respects. In the case of coal, the original organic material that is buried in the ground is plant material. Most of the coal that is found in the world today originates from the Carboniferous Period over 300 million years ago (In the U.S., the Carboniferous is broken up into the Pennsylvanian, in which the coal originates, and the Mississippian, in which limestone was deposited). During this period, there were many low-lying swamps that had large numbers of tree ferns and leafy trees. When these trees died, they fell into the swamp and were fairly quickly covered with sediments. Because of the low oxygen levels in the water in the swamps, this plant material did not decay much and was preserved for later conversion.

Fig. 4: etching depicting some of the significant plants of the Carboniferous period

Another way in which coal differs from oil in creation has to do with the process of conversion. Since the coal started out as wood, it was always a possible fuel source. Even the lowest grade of coal can be burned to produce heat, unlike the microscopic organism that comprised oil. The more conversion that the coal undergoes, the better the grade of coal and the more energy per pound that it can deliver. The process of conversion is similar to oil in that it requires the high temperatures and pressures that are achieved by burial deposition. As the coal gets buried deeper in the earth, water is squeezed from the wood, leaving behind material that is higher in carbon content.

The different amounts of conversion result in different types of coal. There are four main categories of coal: anthracite, bituminous, sub-bituminous, and lignite. These different varieties are rated upon the percentage of carbon in the coal and on their heating value (amount of energy released when burned), which are related to the heat and pressure that the coal underwent in being formed.

Anthracite has the highest heating value and carbon content of any of the coals. It consists of between 86-98% carbon, and has a heating value of about 15,000 Btu’s per pound. When it is burned, it produces very little ash and pollutants other than carbon dioxide. From an energy use perspective, it is the highest grade. There is one big problem with it, though: we have very little of it. Anthracite is found in only 11 counties in Pennsylvania and only constitutes about 2-3% of our known reserves. Its high carbon content means that anthracite coal experience high temperatures and pressure during its existence, which points to most of it being found deep in the earth.

Bituminous coal is the largest single type of coal that we have in the U.S. While its carbon content is less than that of anthracite, it is still reasonably high in the 45-85% range. This gives it a heating value of between 10,000-15,000 Btu's per pound. One of the biggest drawbacks to bituminous coal, though, is that it has a high sulfur content. Most of the bituminous coal formed in swamps that were inundated by seawater. This seawater was high in sulfur, which was left in the coal during the dewatering phase of conversion. When burned, the sulfur in the coal forms sulfur dioxide (a gas), which cannot be filtered and which forms sulfuric acid when it combines with water vapor in the air. This leads to acid rain, which is a serious problem in regions that burn this coal.

Sub-bituminous coal, as one would expect from its name, falls below bituminous coal in both carbon content and heat value. It only contains about 35-45% carbon, and its moisture content lowers its a heating value to between 8,000 and 13,000 Btu's per pound. These lower values are a result of subbituminous coal not being buried very deep in the ground. This coal is found very near to the surface, which means that it is produced via strip-mining. Most of the subbituminous coal in the U.S. currently is found in western states like Wyoming. This is a problem because drier areas like that do not recover very well from stripmining.

Lignite is the lowest value coal of the group. It has a carbon content of 25-35% and contains a lot of moisture, which lowers its heat value to between 4,000 and 8,000 Btu's per pound. Like sub-bituminous, this type of coal has never been buried deep in the ground. It also is found mostly in the West and Southwest, which is somewhat problematic when it comes to stripmining.

Exploration and Production

In the early days of coal usage, exploration was very easy. All that one did was look around to see if there was any seam of coal that intersected the surface. If there was, excavation of the coal began, and the seam was followed into the earth. While down there, one might dig test tunnels into the surrounding rock to see if there were other seams of coal nearby. If any were found, then production would follow into those seams. Otherwise, production would continue on the original seam until either the coal ran out or it became unprofitable to continue.

Today, exploration for coal uses many of the same tools as are used for oil exploration. It does differ in several key respects, though. Coal cannot seep through the pore spaces in sedimentary rock, meaning that one does not need to worry about the presence of a geologic trap. Also, the environments in which coal originally forms (swamps) are radically different from those in which oil forms (ocean). This means that one looks for different types of sedimentary rock features. Lastly, coal needs to be found within a mile or so of the surface in order for it to be extracted profitably, unlike oil that might be 4-5 miles below the surface. This means that one can rely more heavily on surface details for coal than they can for oil.

The process of searching for coal begins by doing detailed geological surveys of the area to see if there is a potential for finding it in the region. This involves stratigraphic studies on the sedimentary layers there. This type of study attempts to determine the extent, age, and depositional environment of the sedimentary rock layers. To aid in this process, core samples might be taken in the region by drilling wells. These core samples can aid in matching up layers over long distances, as well as possibly detecting the presence of coal. Sometimes, enough evidence is found from this type of study to go forward with a mine. However, the information might be backed up with a seismic survey of the area to confirm the size and locations of coal in the subsurface. It might also help to decide on the best approach for extracting the coal.

Fig. 5: core sample from a well (USGS)

The method of production of the coal depends greatly upon its location in the ground. If the coal is found within several hundred feet of the surface, then the most reasonable method of extraction is strip-mining. This process involves removing all of the sediment and rock that lies over the coal in order to expose it. The coal is then scooped from the ground using very large cranes and trucks and driven directly to trains that take it to market. When all of the coal is removed from a location, federal law mandates that the land be remediated to its previous state. The means that the removed sediment and rock is put back in place, and vegetation is planted.

If the coal is much deeper than several hundred feet below the surface, the best method for extraction is a traditional underground mine. The process of mining, though, is anything but traditional. Today's mining operations rely on heavy tunneling equipment to extract the coal instead of dynamite, pickaxe, and shovels. Figure 6 shows a picture of a longwall miner operating in Utah. In this type of operation, large rectangular blocks of coal are apportioned within the seam and then carved out by cutting paths through it. The large blocks are then removed in one continuous cutting by the machinery as it moves back and forth across the block face[9].

Fig. 6: longwall miner (BLM)

Operations like this pose several hazards, though. One is that the mine might cave in as supporting coal is removed. This is generally taken care of by large hydraulic systems that support the mine while operations are in process. There is also the hazard of explosion from methane gas and coal dust that build up in the air. As the coal is cut, methane that is trapped in the coal is released, and small chips of flammable dust get into the air. These two are ameliorated by spraying water to knock down the dust and ventilating the air with the outside air to insure that methane levels do not reach dangerous levels.

In 2012, there were 1,207 mines in the U.S. that produced about 1.0 billion short tons of coal[8]. The overwhelming majority of this coal comes from surface mines (either strip mines or mountaintop removal), as it is much easier to recover. Surface mines produced 672 million short tons of coal, while the underground mines produced 342 million short tons. Of course, all of this coal was of differing quality. The underground mines almost exclusively produced the higher heating value bituminous and anthracite, while many strip mines produced sub-bituminous and lignite.

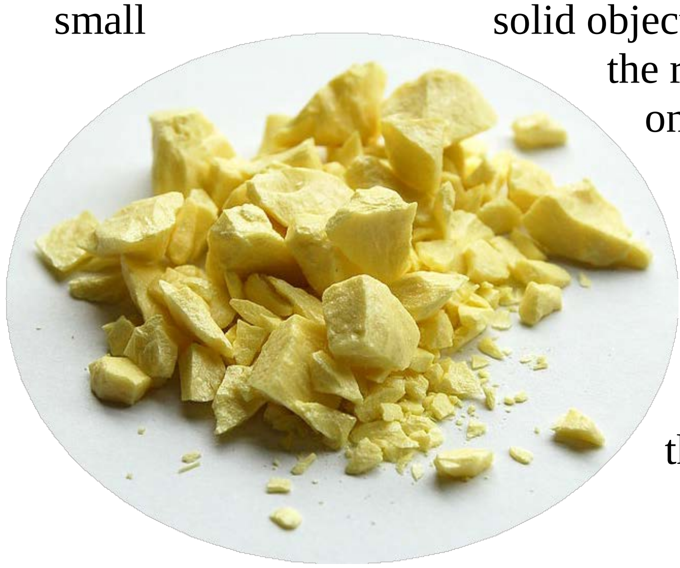
The environmental impact of this is activity can be very severe. The Western strip mines are in locations that get 20 inches or less of rain per year. The soils and organisms that are found on the surface there have taken a long time to develop. There is no good way of preserving the topsoil that is removed there to get at coal, which means that remediating the area to its natural setting is almost impossible. Without the proper soils, the plants and animals in the region will take a long time to recover from this mining, if they ever do.

While subsurface mines do not have the same problems as strip mines, they can have an enormous impact. Cave-ins in the mine after production stops can cause massive slumping and subsidence on the surface above the mine. Fires can erupt in the mine and burn for many years, as oxygen is able to get to the coal through shafts to keep it burning. Water that runs through the mine leaches heavy metals and other ions from the rock and deposits these in the local water system. Tailings and waste sludge from the mine are often put into large pond impoundments outside of the mine, leaching tarry substances and heavy metals into the local system. Occasionally, the dams on these ponds can fail, releasing large quantities of waste products into the local river systems. In October of 2000, the dam at the Martin County Coal Corporation's impoundment dam failed, releasing 250,000 million gallons of fluid and over 150,000 cubic yards of sludge into the Tug Fork of the Big Sandy River in Inez, Kentucky. This devastated a 75 mile stretch of the river, killing wildlife and releasing measurable quantities of heavy metals that effectively cut off drinking water in the area[10].

Cleaner Burning Technology

The effect of mining can be severe, but it is usually localized; the effect of burning coal can be both severe and global. Unlike nuclear power plants that retain all but their waste heat inside, coal burning plants emit an array of products to the external environment. The by-products of burning fall into two different categories: particulate matter and gaseous pollutants. The greatest quantity of this waste is in the form of carbon dioxide, a greenhouse gas that is expected to be produced in the exothermic reaction of carbon and oxygen. If coal were 100% carbon and enough oxygen was delivered to the coal during burning, this would be the only byproduct other than heat. All of the other pollutants are a result of coal not being pure carbon and of the combustion not being total.

One of the more easily removed pollutants from burning coal is ash. It is produced by the non-combustible components that are found in the coal. The higher-grade coals, such as anthracite, generally have less of these than the lower-grade coals, such as lignite. Depending upon what type is being burned, anywhere from about 5% to 22% of the coal will be converted to ash, with a nationwide average of about 9%[11]. Since the ash is solid matter, it can be removed by filtration, by water spray of the flue gas, by cyclonic precipitators, or a host of other products that will capture small solid objects. The biggest question with the removal of ash is how much one is willing to pay.



As stated in the Coal Creation section, bituminous coal has sulfur in it (about 1-2% by weight), which gets converted to sulfur dioxide in the burning and then into sulfuric acid when it combines with water vapor. Its removal is not as straightforward as ash. If the sulfur has combined with iron in the coal to make iron pyrite (fool's gold), it can be removed by crushing the coal and washing it in large vat of water. The coal, which is less dense than water, floats to the surface while the heavy iron pyrite sinks to the bottom. If the sulfur is in some molecular form that is attached to the carbon, the removal is not quite as easy. The sulfur can be removed from the carbon chemically before it is burned, but this process is fairly expensive. Instead, the latest technology seeks to remove the sulfur after the combustion has taken place. This can be done by passing the flue gas through a mixture of limestone and water, which causes the sulfur to react with the calcium carbonate to form calcium sulfate, or gypsum. When dried, this compound can be used to make wallboard.

The other pollutants that come from the burning of coal are produced by sub-optimal burning conditions. If there is not enough oxygen in the combustion chamber, then carbon monoxide can be created. In enclosed spaces, carbon monoxide is extremely hazardous, as the molecule displaced oxygen in hemoglobin and causes asphyxiation. As long as the flue gases are being adequately vented to the outside world and mixed with other air, this hazard is not too likely to affect anyone. However, carbon monoxide does combine with water vapor to form carbonic acid, and thus increases the acidity of rainfall.

If the combustion chamber is hot enough (above 2800 ^{o}F) and there is too much oxygen, then nitrogen that is in the air will combine with oxygen to form nitrogen oxide compounds (NOx). These pollutants are responsible for several different problems. They are responsible for the greenish brown haze that one sees in many cities that are experiencing temperature inversions. If they combine with water vapor, they can form nitric acid and increase the acidity of rain. If they combine with volatile organic compounds in the presence of sunlight, they will create ground level ozone, which is responsible for numerous health problems in humans.

This pollutant can be eliminated by making sure that the combustion temperature does not go above 2800 ^{o}F while there is much nitrogen in the chamber. In modern power plants, this is done by burning the coal in “staged combustion” chambers. The coal is first burned in a chamber that is maintained at a lower temperature as long as there are significant amounts of nitrogen present (some nitrogen is bound in the coal). Once the nitrogen levels are reduced, the coal is moved to another stage where it is burned at a higher temperature. These types of chambers can reduce by 40-70%[12]. While this is good, it is not good enough to reach new restrictions of the Clean Air Act for cities that have been failing to meet air quality standards. This means that more research needs to be done on cleaning the pollutants out of the flue gases if coal continues to be used in these regions.

Coal Fluidization

As the previous section points out, burning coal cleanly is a problem. Another problem is using coal for anything other than a heat source in a static plant. The solid nature of coal makes it impractical to use in any type of mobile situation, such as a car, bus, or plane. Even our traditional image of coal being used in the train industry is problematic, as it requires someone to constantly monitor the heat of the boiler and to manually add coal to keep the flame going. The train industry converted to diesel-powered motors many decades ago, even though trains are the primary method for transporting coal.

Both of these problems can be skirted if the coal is turned into a fluid fuel. We already know how to remove sulfur and other contaminants from fluids, as we do this all the time with sour crude oil or natural gas (the sour part is sulfur) through chemical and distillation means. Transporting a fluidized coal could be done through existing pipelines, and it could readily be used in mobile transportation.

There are two methods for converting coal into a fluid fuel: coal gasification and coal liquefaction. The objective of coal gasification is to convert coal into a combustible gas, such as methane, while the goal of coal liquefaction is to change coal into synthetic petroleum. The processes to obtain these can vary depending upon the desired products and the expense.

The cheapest way to achieve coal gasification is to heat coal in the absence of air. If this is done, the carbon in the coal combines with hydrogen in the coal (in the form of moisture) to create methane. This process was used extensively in the early 1900's to produce the coal gas that was used to light lamps. This process does not convert much of the coal, though, leaving about 80% of it behind as char. To more fully convert the coal, it must be heated above 800 ^{o}C in the presence of steam. If this is done, the carbon and water are converted to carbon monoxide (CO) and hydrogen gas. While this combination will burn, it cannot be used in processes that require methane. A second stage called methanation will convert one carbon monoxide molecule and three hydrogen molecules into one methane molecule and water. The gasification process can be done in a single step if the coal is heated in the presence of hydrogen gas initially. However, since no one has a ready supply of hydrogen gas that can be produced cheaply, this is rarely done.

Coal liquefaction can be done by one of two different methods. The first method was developed by the Germans during World War II after they were rebuffed in North Africa and Russia and were desperate for oil to run their tanks and planes. This method uses the initial stage of coal gasification (convert coal to carbon monoxide and hydrogen gas) followed by a second stage that uses temperature, pressure, and a catalyst to convert the mixture into a broad range of hydrocarbons, depending upon what settings are used. This second stage, called the Fischer-Tropsch synthesis, allowed the Germans to create over 200 million gallons of fuel per year at the end of the War. The second method for coal liquefaction is a direct method that uses coal, hydrogen, and a catalyst at extreme pressures and temperature. This method can create a rough synthetic crude oil that can be refined for gasoline, diesel, or fuel oils.

The economics of both of these fluidization techniques made them relatively unused for most of the past 40 years. During the 1970's, we were putting money into research and building test plants for both of these. With the plummeting oil prices of the 1980's and 1990's, there was no need to look at these. However, with the price of oil increases and the need for more energy security, these methods are economical once again. Several test facilities and demonstrator plants are currently being built at various locations in the U.S.[13]

Discussion Questions

1. What is the best kind of coal? Why?

2. What is the most abundant form of coal? What is the least abundant?

3. Could we develop an environmentally friendly method for finding and extracting coal?

4. Given the large supply of coal in the U.S., should we use more of it to meet our energy needs Why or why not?

5. Realizing that converting coal to synthetic methane or petroleum depletes the available energy in the coal, should we do more or less coal gasification and/or coal liquefaction?

6. What type of fuel does the nearest electrical power plant use?

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Additional Reading

The following link goes to the Department of Energy’s program on developing new power systems for converting coal to electricity. It discusses research into making systems more energy efficient and less polluting.

Department of Energy

Topic: Clean Coal Research

Summary: Contains information about how the electric power systems and attempts to make them more energy efficient and less polluting.

Link: http://energy.gov/fe/science-innovation/clean-coal-research

The following link discusses coal resources, mining, and usage. It contains detailed maps of coal locations, as well as assessments of recoverable reservoirs. The site is maintained by U.S. Geological Survey.

U.S. Geological Survey

Topic: Energy Resource Program - Coal

Summary: Contains information about coal resources, mining, and usage

Link: http://energy.usgs.gov/coal.html