

ESA21

Environmental Science Activities for the 21st Century

Fossil Fuels: Coal

Introduction

History

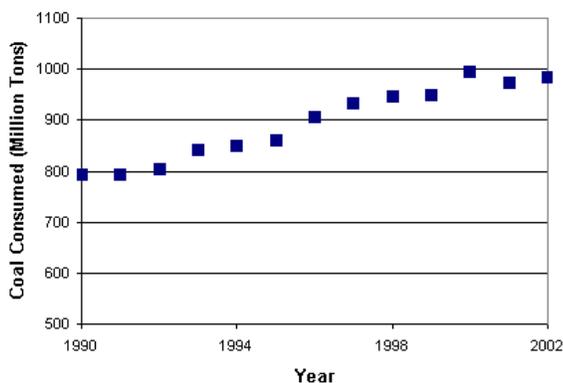
Coal has been a source of energy for almost as long as Homo sapiens have inhabited the planet. The earliest record for its use dates back more than 3000 years to China where it may have been used to smelt copper¹. In areas where coal seams intersected the surface, coal was a ready supply of energy just 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 Era². Its earliest use in the U.S. was in the 1300's by Hopi Indians in the desert Southwest for cooking and pottery-making³.

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 led 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.

Usage

Today, coal is still the energy of choice for many applications in the U.S. The reason for this is that we have a large and readily available supply of it, and can produce it very cheaply, as long as the cost of repairing the damage done by mining and using it are not considered. We currently use a little 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 alone⁴, 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 (91%) goes toward the generation of electricity for sale to the public. It currently accounts for a little over 50% of the electricity generated in the U.S.⁵ While this percentage has stayed relatively fixed for the last decade, Figure 1 shows that the use of coal for this process has been growing as the demand for more electricity has risen. This average increase of 1.9% a year almost exactly matches the percentage increase in public electricity demand over that same time period.

Figure 1: Coal consumed for electricity⁶

Coal does get used for other purposes, although some of these uses get mixed with generating electricity. About 6% 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 .5% 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 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 (2001) (Thousand Short Tons)	
State	Amount
Wyoming	368,749
West Virginia	162,416
Kentucky	133,834
Pennsylvania	74,146
Texas	45,042

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 17 mines, this state produces over 350 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 162 and 133 million short tons in 2001, respectively, from over 700 mines in total. The combined output from these three states is about two thirds of our total output⁷.

Figure 2: Top coal states

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.

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, subbituminous, 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 conversion⁸. 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.

Subbituminous 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. is found in western states like Wyoming. This is a problem because drier areas like that do not recover very well from strip-mining.

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 subbituminous, 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 strip-mining.

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.



Figure 3: Core sample from a well (USGS)



Figure 4: Strip mine in the Gulf Coast (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. This 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 5 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 face⁹. 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.



Figure 5: Longwall miner (BLM)

In 2001, there were 1,478 mines in the U.S. that produced over 1.1 billion short tons of coal. Of these, 719 were underground mines and 757 were strip mines⁷. While the split on these two was about 50/50, the amount of coal produced was not. Strip mines produced 745 million short tons of coal, while the underground mines produced only 390 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 the strip mines produced subbituminous and lignite.

The environmental impact of this activity can be very severe. A good number of the 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 area¹⁰.

Cleaner Burning Technology

The effect of mining can be severe, but it is usually localized. The effect of burning coal can be both sever 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 was 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

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. 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 °F) and there is too much oxygen, then nitrogen that is in the air will combine with oxygen to form nitrogen oxide compounds (NO_x). 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 °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.

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: Electric Power Systems Summary: Contains information about how the electric power systems and attempts to make them more energy efficient and less polluting. Link: http://www.fe.doe.gov/programs/powersystems/
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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.

 USGS	Topic: Energy Resource Program - Coal Summary: Contains information about coal resources, mining, and usage Link: http://energy.er.usgs.gov/NCRA/
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Activity

For this week’s activity, we are going to investigate the ash content of various varieties of coal¹³. This will be done by exposing samples of coal to high heat to allow the carbon in the coal to react with oxygen, and then measuring the amount of material that is left behind. In order to do this lab, you will need to acquire different types of coal samples. The can be done through a scientific equipment supply company, such as Ward’s Scientific, that sell peat, lignite, and bituminous coal in bulk. You will also need a mortar and pestle, a mass balance, a crucible, a vent hood, and a burner.

1. Clean and dry the crucible in an oven. Allow it to cool before handling.
2. Crush each coal sample into very small chunks (millimeter or so in diameter), and keep separate.
3. Measure the mass of the crucible and record it on the activity sheet.
4. Place a small sample one of the coals (1-2 grams) into the crucible and place the lid on it. Measure the mass of the combination, and record it on the activity sheet.
5. Turn on the ventilation hood and the burner. Make sure that the burner is operating under optimal (hot) conditions.
6. Put the crucible over the burner and heat it for 15-25 minutes. Very carefully check that the sample has thoroughly decomposed (do not allow the ash to fly out). If it has not, return the crucible to the flame and heat for 5 more minutes or until the sample looks thoroughly decomposed.

7. After the crucible cools, place it on the scale and measure its mass. Record it on the activity sheet.
8. Clean the crucible again, dry it, and repeat the above procedure with your other samples.
9. When finished, be sure to turn off the flame and the vent hood.
10. Make the calculations on the activity sheet and answer questions.

References

- 1 <http://www.energyquest.ca.gov/story/chapter08.html>, October 25, 2003.
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- 3 http://www.fe.doe.gov/education/energylessons/coal/coal_history.html, October 25, 2003.
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- 5 http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html, October 25, 2003.
- 6 <http://www.eia.doe.gov/cneaf/electricity/epm/chap2.pdf>, October 27, 2003.
- 7 <http://www.eia.doe.gov/cneaf/coal/page/acr/table1.html>, October 25, 2003.
- 8 http://www.fe.doe.gov/education/energylessons/coal/coal_howformed.html, October 27, 2003.
- 9 <http://www.uow.edu.au/eng/current/longwall/history.htm>, October 30, 2003.
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- 11 <http://www.eia.doe.gov/cneaf/electricity/epav2/epav2t25.txt>, October 25, 2003.
- 12 http://www.fe.doe.gov/programs/powersystems/pollutioncontrols/overview_noxcontrols.shtml, October 30, 2003.
- 13 <http://www.coaleducation.org/lessons/sec/properties/coalash.htm>, October 31, 2003.

ESA21: Environmental Science Activities

Name:

Sample	Mass of Crucible	Mass of Crucible + Coal	Mass of Crucible + Ash

Equations:

$$\text{Mass of ash} = (\text{Mass of crucible + ash}) - (\text{Mass of crucible})$$

$$\text{Mass of coal} = (\text{Mass of crucible + coal}) - (\text{Mass of crucible})$$

$$\text{Percentage ash} = 100\% * (\text{Mass of ash})/(\text{Mass of coal})$$

Calculations:

Sample	Mass of Ash	Mass of Coal	Percentage Ash

1. Which one of the coal samples had the least percentage of ash? Did you expect this? Why or why not?

2. Does this procedure account for all of the ash that an electric power plant might have when they burn this coal? What factors are involved in burning coal for electricity that might increase or decrease the amount of ash?

3. Take some of you ash and place it in water. Does it dissolve? Could you use a water spray to eliminate ash from the flue gas?