PDHonline Course E347 (4 PDH)

Coal Fired Steam Plants

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Coal Fired Steam Plants

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Introduction

For over 100 years coal fired power plants have provided a stable source of electricity that provides vast quantities of inexpensive, reliable power. Historically, coal-fired generation gas accounted for over 50% of the electricity generated in the U.S. The generation mix has been changing in recent years due to low-cost natural gas and some impact from renewable energy sources. Presently coal is less around 30% of the total fuel mix with natural gas the pre-dominate source at 34%. The known coal reserves are expected to last for centuries at the current rates of usage. See Figure 1 for a breakdown of electricity generation by fuel type.

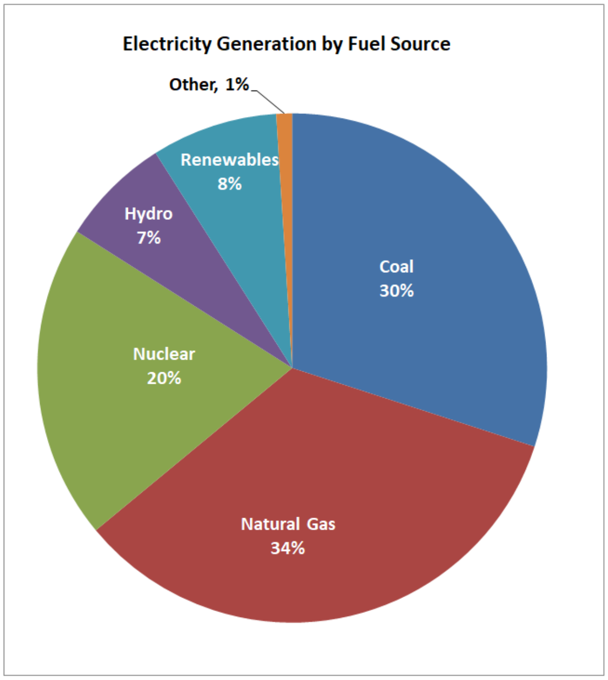


Figure 1

Coal power is a rather simple process. In most coal fired power plants, chunks of coal are crushed into fine powder and are fed into a combustion unit where it is burned. Heat from the burning coal is used to generate steam that is used to spin one or more turbines to generate electricity.

Coal has played a major role in electrical production since the first power plants that were built in the United States in the 1880's.

The earliest power plants used hand fed coal to heat a boiler and produce steam. This steam was used in *reciprocating steam engines* which turned generators to produce electricity. In 1884, the more efficient high speed *steam turbine* was developed which replaced the use of steam engines to generate electricity. In the 1920s, the pulverized coal firing was developed. This process brought advantages that included a higher combustion temperature, improved thermal efficiency and a lower requirement for excess air for combustion. In the 1940s, the cyclone furnace was developed. This new technology allowed the combustion of poorer grade of coal with less ash production and greater overall efficiency.

Coal is pulverized into a fine powder stems because, if the coal is made fine enough, it will burn almost as easily and efficiently as a gas. The coal is crushed between balls or cylindrical rollers that move between two tracks or "races." The raw coal is then fed into the pulverizer along with air heated from the boiler. As the coal gets crushed by the rolling action, the hot air dries it and blows the usable fine coal powder out to be used as fuel. The powdered coal from the pulverizer is directly blown to a burner in the boiler. The burner mixes the powdered coal in the air suspension with additional pre-heated combustion air and forces it out of a nozzle. Under operating conditions, there is enough heat in the combustion zone to ignite all the incoming fuel.

Cyclone furnaces were developed after pulverized coal systems and require less processing of the coal fuel. They can burn poorer grade coals with higher moisture contents and ash contents. The crushed coal feed is either stored temporarily in bins or transported directly to the cyclone furnace. The furnace is basically a large cylinder jacketed with water pipes that absorb the some of the heat to make steam and protect the burner itself from melting down. A high powered fan blows the heated air and chunks of coal into one end of the cylinder. At the same time additional heated combustion air is injected along the curved surface of the cylinder causing the coal and air mixture to swirl in a centrifugal "cyclone" motion. The whirling of the air and coal enhances the burning.

Coal-fired technology has improved the heat rates of coal plants from over 138,000 BTU/kWh in the 1880’s to less than 10,000 BTU/kWh today.

We will start this course with an overview of the coal industry followed by a detailed explanation of the components of a coal-fired steam plant and we will conclude with a look at the environmental issues associated with a coal-fired steam plant.

Chapter 1
Coal as a Fuel Source

Coal is a fossil fuel formed from plant remains that were preserved by water and mud from biodegradation. Coal is a readily combustible black or brownish-black rock. It is composed primarily of carbon and hydrogen along with small quantities of other elements, notably sulfur. Coal is extracted from the ground by coal mining, either underground mining or open pit mining.


Photo courtesy DOE

Coal is the largest source of fuel for the generation of electricity world-wide and is the largest natural energy source in the United States. Coal is also the largest world-wide source of carbon dioxide emissions and it may be contributing to climate change and global warming. In terms of carbon dioxide emissions, coal is slightly ahead of petroleum and about double that of natural gas.

Coal has been used as a fuel source for thousands of years; the Chinese mined coal stone for fuel 10,000 years ago at the time of the New Stone Age. The development of the Industrial Revolution led to the large-scale use of coal, as the steam engine took over from the water wheel as the prime mover in industrial plants.

Coal is primarily used as a solid fuel to produce electricity and heat through combustion. World coal consumption is about 6.2 billion tons annually, of which about 75% is used for the production of electricity.

When coal is used for electricity generation, it is usually pulverized and then burned in a furnace with a boiler. The furnace heat converts boiler water to steam, which is then used to spin turbines which turn generators and create electricity. The thermodynamic efficiency of this process has been improved over time. Traditional steam turbines have topped out with some of the most advanced units reaching about 35% thermodynamic efficiency for the entire process, which means 65% of the coal energy is waste heat that is released into the surrounding environment. Older coal power plants are significantly less efficient and produce higher levels of waste heat.

Approximately 40% of the world electricity production uses coal. It is estimated that the total known coal deposits recoverable by current technologies might be sufficient for around 250-300 years' use at current consumption levels.

Types of Coal

We use the term "coal" to describe a variety of fossilized plant materials, but no two coals are exactly alike. Heating value, ash melting temperature, sulfur and other impurities, mechanical strength, and many other chemical and physical properties must be considered when matching specific coals to a particular application.

Coal is classified into four general categories, or "ranks." They range from lignite through sub-bituminous and bituminous to anthracite, reflecting the progressive response of individual deposits of coal to increasing heat and pressure. The carbon content of coal supplies most of its heating value, but other factors also influence the amount of energy it contains per unit of weight. (The amount of energy in coal is expressed in British thermal units per pound. A BTU is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.)

About 90 percent of the coal in the U.S. falls in the bituminous and sub-bituminous categories, which rank below anthracite and, for the most part, contain less energy per unit of weight. Bituminous coal predominates in the Eastern and Mid-continent coal fields, while sub-bituminous coal is generally found in the Western states and Alaska. Lignite ranks the lowest and is the youngest of the coals. Most lignite is mined in Texas, but large deposits also are found in Montana, North Dakota, and some Gulf Coast states.

Anthracite

Anthracite is coal with the highest carbon content, between 86 and 98 percent, and a heat value of nearly 15,000 BTUs-per-pound. Most frequently associated with home heating, anthracite is a very small segment of the U.S. coal market. There are 7.3 billion tons of anthracite reserves in the United States, found mostly in 11 northeastern counties in Pennsylvania.

Bituminous

The most plentiful form of coal in the United States, bituminous coal is used primarily to generate electricity and make coke for the steel industry. The fastest growing market for coal is supplying heat for industrial processes. Bituminous coal has a carbon content ranging from 45 to 86 percent carbon and a heat value of 10,500 to 15,500 BTUs-per-pound. The carbon content of bituminous coal is around 60-80%; the rest is composed of water, air, hydrogen, and sulfur. Bituminous coal is a relatively soft coal containing a tarlike substance called bitumen. It is of higher quality than lignite coal but poorer quality than anthracite coal.

Bituminous coal is usually black, sometimes dark brown, often with well-defined bands of bright and dull material. Bituminous coal seams are identified by the distinctive sequence of bright and dark bands and are classified accordingly as either "dull, bright-banded" or "bright, dull-banded" and so on.

Bituminous coals are graded according to reflectance, moisture content, volatile content, plasticity and ash content. Generally, the highest value bituminous coals are those which have a specific grade of plasticity, volatility and low ash content, especially with low carbonate, phosphorus and sulfur.

Plasticity is vital for coking as it represents its ability to gradually form specific plasticity phases during the coking process. Low phosphorus content is vital for these coals, as phosphorus is detrimental to steel making.

Coking coal is best if it has a very narrow range of volatility and plasticity. Volatile content and swelling index are used to select coals for coke blending as well.

Volatility is also critical for steel-making and power generation, as this determines the burn rate of the coal. High volatile content coals, while easy to ignite often are not as prized as moderately volatile coals; low volatile coal may be difficult to ignite although it will contain more energy per unit volume. The smelter must balance the volatile content of the coals to optimize the ease of ignition, burn rate, and energy output of the coal.

Low ash, sulfur, and carbonate coals are good choices for power generation because they do not produce much boiler slag and they do not require as much effort to scrub the flue gases to remove particulate matter. Carbonates are detrimental to the boiler apparatus because they stick to the equipment. Sulfide contents are also detrimental to some degree as this sulfur is emitted and can form smog, acid rain and haze pollution. Scrubbers on the flue gases are used to eliminate particulate and sulfur emissions.

When used for industrial processes, bituminous coal must first be "coked" to remove volatile components. Coking is achieved by heating the coal in the absence of oxygen, which drives off volatile hydrocarbons such as propane, benzene and other aromatic hydrocarbons, and some sulfur gases. This also drives off the amount of the contained water of the bituminous coal.

Coking coal is used in the manufacture of steel, where carbon must be as volatile-free and ash-free as possible.

Bituminous coal is mined in the Appalachian region, primarily for power generation. Mining is done via both surface and underground mines.

Sub-bituminous

Ranking below bituminous is sub-bituminous coal with 35-45 percent carbon content and a heat value between 8,300 and 13,000 BTUs-per-pound. Reserves are located mainly in a half-dozen Western states and Alaska. Although its heat value is lower, this coal generally has a lower sulfur content than other types, which makes it attractive for use because it is cleaner burning.

Sub-bituminous coal is a type of coal whose properties range from those of lignite to those of bituminous coal and is used primarily as fuel for steam-electric power generation.

Sub-bituminous coal may be dull, dark brown to black, soft and crumbly at the lower end of the range, to bright, jet-black, hard, and relatively strong at the upper end. It contains 20-30% inherent moisture by weight. A major source of sub-bituminous coal in the United States is the Powder River Basin in Wyoming.

Its relatively low density and high water content renders some types of sub-bituminous coal susceptible to spontaneous combustion if not packed densely during storage in order to exclude free air flow.

Lignite

Lignite is a geologically young coal which has the lowest carbon content, 25-35 percent, and a heat value ranging between 4,000 and 8,300 BTUs-per-pound. Sometimes called brown coal, it is mainly used for electric power generation.

It is the lowest rank of coal and used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 66%, and very high ash (50%) content compared with bituminous coal. It is also a heterogeneous mixture of compounds for which no single structural formula will suffice.

Because of its low energy density, brown coal is inefficient to transport and is not traded extensively on the world market compared with higher coal grades. It is often burned in power stations constructed very close to any mines. Carbon dioxide emissions from brown coal fired plants are generally much higher than for comparable black coal plants.

Lignite can be separated into two types. The first is *fossil wood* and the second form is the *compact lignite* or perfect lignite. Fossil wood is barely classified as coal and is a very marginal coal feedstock with a heat rate of less than 6,300 BTU's. While still an inefficient coal, compact lignite has a heat rate of greater than 6,300 BTU's.

Energy density

The energy density of coal can be expressed in kilowatt-hours per pound (kWh/lb) of coal. The energy density of coal is about 3 kWh/lb of coal. When you consider that the thermal efficiency of a coal-fired power plant is about 30% then the only about 0.91 kWh's are produced for each pound of coal burned. The remainder is given up as waste heat and other losses in the generation process. Said another way, it takes about 1.1 pounds of coal to generate one kWh. Each kilowatt-hour produced also generates about 2 pounds of CO_2.

To put this in laymen's terms, consider the energy required to light a 100-watt incandescent light bulb for one year assuming 4-hours use per day. It will require 146 kWh's per year (100 * 4 * 365 / 1,000 = 146) to light the lamp for four hours per day for one year. Since it takes 1.1 pounds of coal per kWh, 160 pounds of coal will be required and almost 300 pounds of CO_2 will be generated. In comparison, an equivalent compact fluorescent lamp is only 23 watts and will only use 34 kWh's per year, 37 pounds of coal, and about 70 pounds of CO_2.

Another interesting comparison is the CO_2 generated from coal versus other sources. As we mentioned, coal-fired generation results in about 2 lbs/kWh of CO_2. For oil-fired generation it is slightly less than 2 lbs/kWh and for natural gas, the CO_2 emissions are about 1.1 lbs/kWh. For nuclear power, the CO_2 are miniscule, perhaps 0.1 lbs/kWh.

World coal reserves

The recoverable coal reserves are estimated to be around 900 billion tons. This is equal to about 4,417 billion barrels of oil equivalent (BBOE). The annual coal consumption is about 46 million barrels of oil or 17 BBOE. If consumption continues at this rate the reserves will last 260 years. As a comparison, natural gas provides 51 million BOE and oil provides 76 million barrels per day.

United States Coal Reserves

Of the three fossil fuels, coal has the most widely distributed reserves; coal is mined in over 100 countries, and on all continents except Antarctica. The largest reserves are found in the United States, Russia, Australia, China, India and South Africa. In the continental United States, the coal largest reserves are divided into eleven geographic regions. They are,

1. Northern Appalachian
2. Central Appalachian
3. Southern Appalachian

4. Gulf
5. Illinois Basin
6. Western Interior
7. Plains (also called North Dakota Lignite)
8. Powder River Basin
9. Rockies
10. Southwest
11. Northwest

The following graphic shows the supply and percent of the U.S. coal reserves by region.

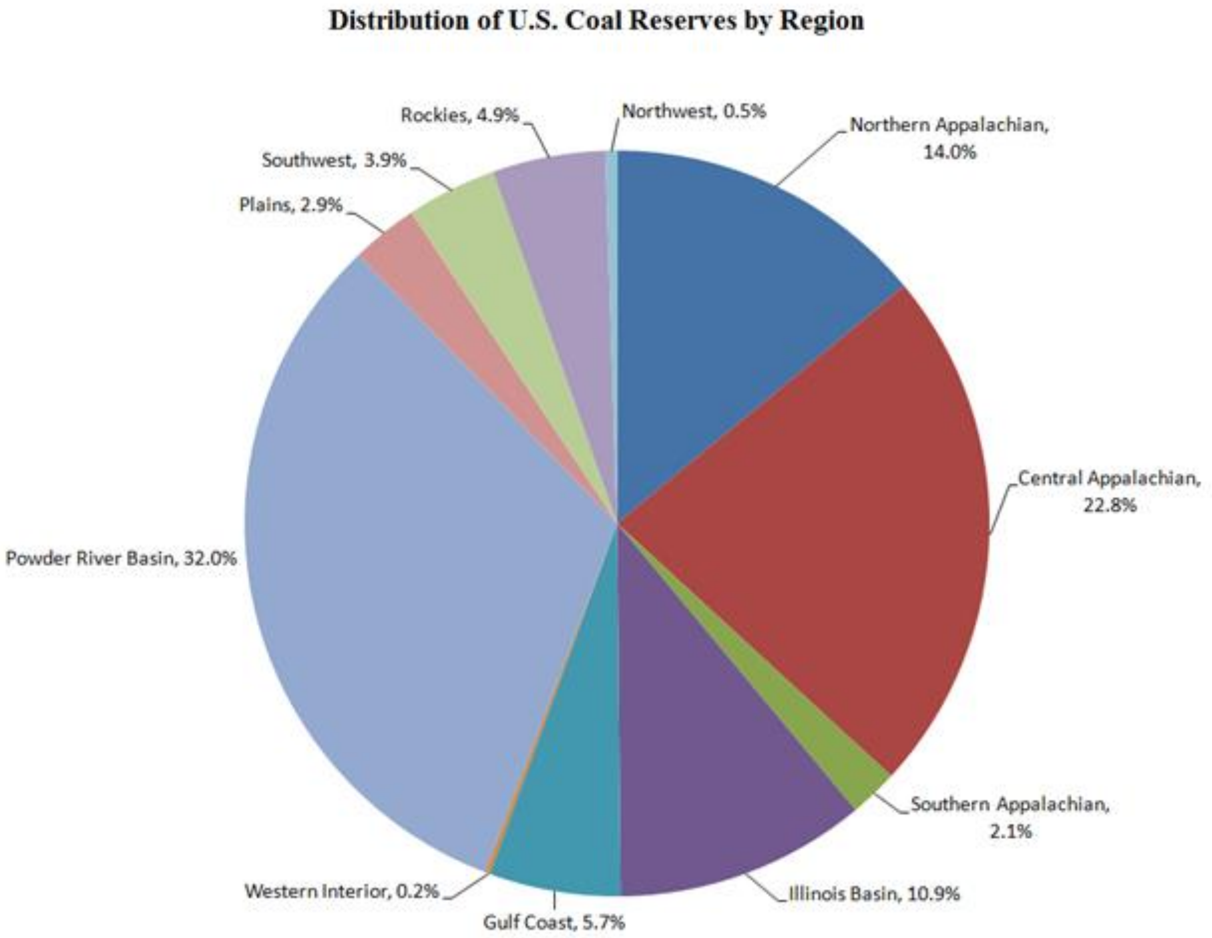


Figure 2

As you can see from the chart, the Powder River Basin, North Appalachian, and Central Appalachian coal make up the bulk of the U.S. coal reserves. Figure 2 on the next page shows each of these regions on a map of the United States.

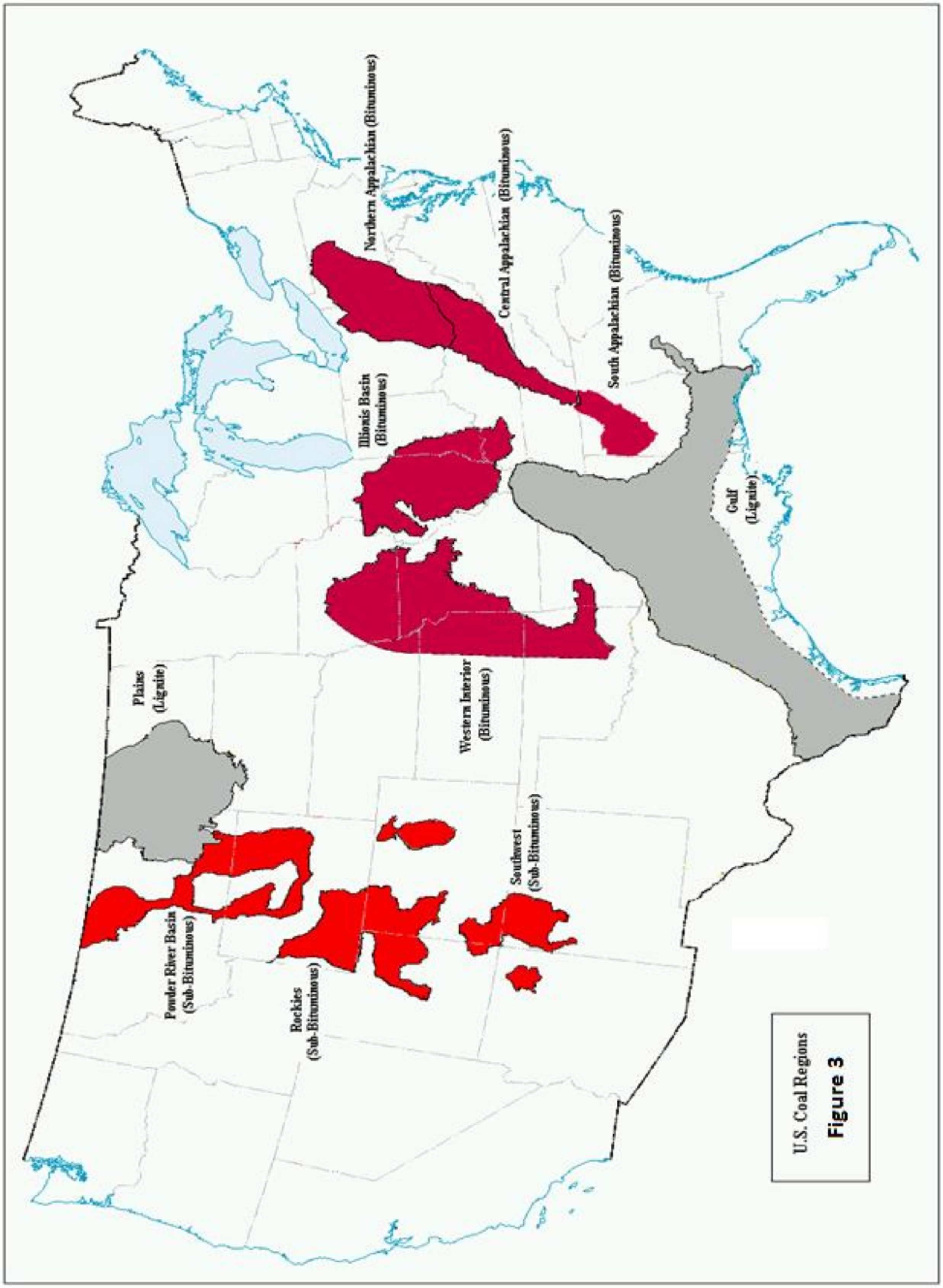
The following is a discussion of a few of the major coal areas in the country.

Northern Appalachian

Coal from the Northern Appalachian region is predominately bituminous. It includes the states of Pennsylvania, Ohio, Maryland, and portion of West Virginia. About 60% of Northern Appalachian coal comes from the Pittsburgh seam, which is a large reserve of coal that runs throughout the area.

Central Appalachian

Central Appalachian coal is low sulfur bituminous coal. This region includes portions of Kentucky, West Virginia, Virginia, and Tennessee. Because of the low sulfur content of Central Appalachian coal it has been widely used in power plants that have not been retrofitted with pollution control scrubbers. Coal from this region tends to run in narrow seams and mines are exhausted quickly, requiring new mines to be built. The area has been mined extensively and finding new areas to mine, and getting them permitted is getting more difficult.



U.S. Coal Regions

Figure 3

Southern Appalachian

Alabama and Tennessee make up the Southern Appalachian coal region. This is an area of bituminous coal.

Gulf Coast

The Gulf coast covers a wide swath of Southern states including Texas, Louisiana, Arkansas, Mississippi, Northern Florida, and Alabama. This is an area of lignite and was used for many years for power production. Many of the sources are nearing depletion, but the area has an abundance of untapped reserves. Many IGCC plants are considering Gulf lignite as a feedstock.

Illinois Basin

The states of Illinois, Indiana, and Western Kentucky comprise most of the Illinois Basin. The Illinois Basin is an area of bituminous coal that is relatively high in sulfur content. However, there are a few low sulfur areas in the Illinois Basin. This area has not been extensively mined and large reserves exist, especially of high sulfur content coal.

Western Interior

The six states of Arkansas, Oklahoma, Kansas, Missouri, Nebraska, and Iowa make up the Western Interior coal area. This area is predominately bituminous coal. The area is comprised of three major basins and has significant coal reserves.

Powder River Basin

The Power River Basin (PRB) includes Northern Wyoming and Southeast Montana. It is a large area of sub-bituminous coal. It has the advantage of being easy to access from surface mines and has relatively thick seams and is a low sulfur coal. The disadvantage is that the PRB is not near major load centers and the coal must be transported long distances to the power plants.

Table 1 has the characteristics of a few of the coal from four of the regions.

Table 1
Comparison of Coal Characteristics by Region
(by percent, except BTU values)

Properties	Appalachian	Illinois Basin	Powder River Basin	Gulf Coast
Moisture	5.20	12.20	30.24	26.80
Carbon	73.80	61.00	48.18	45.82
Hydrogen	4.90	4.25	3.31	3.11
Nitrogen	1.40	1.25	0.70	0.70
Chlorine	0.07	0.07	0.01	n/a
Sulfur	2.13	3.28	0.37	0.69
Oxygen	5.40	11.00	11.87	14.68
Ash	7.10	6.95	5.32	8.20
Heat Content (BTU)	13,260	10,982	8,340	7,810

From Table 1 we see that the Appalachian coal has the highest BTU value with a sulfur content of slightly over 2%. In comparison, the Powder River Basin coal has a much lower BTU content (8,340), but has a sulfur content of only 0.37% while the Illinois Basin coal has a moderately good BTU content of 10,982 and very high sulfur content at over 3%.

Chapter 2
Coal-Fired Steam Plant Designs

Coal-fired steam plants are designed on a large scale for continuous operation. These plants have some kind of rotating machinery to convert the heat energy of combustion into mechanical energy, which then operate an electrical generator. The *prime mover* is a steam turbine. The plants operate on the principal of the drop between the high pressure and temperature of the steam and the lower pressure of the atmosphere or condensing vapor in the steam turbine.

In a coal-fired power plant the chemical energy stored in the coal and oxygen of the air is converted successively into thermal energy, mechanical energy and, finally, electrical energy for continuous use and distribution across a wide geographic area. Each fossil fuel power plant is a highly complex, custom-designed system. Multiple generating units may be built at a single site for more efficient use of land, natural resources and labor.

Coal fired power plants produce waste. These byproducts must be considered in both the design and operation of the plants. Waste heat due to the finite efficiency of the power cycle must be released to the atmosphere, often using a cooling tower, or river or lake water as a cooling medium, especially for condensing steam. The flue gas from combustion of the fossil fuels is discharged to the air; this contains carbon dioxide and water vapor, as well as other substances such as nitrogen, nitrogen oxides, sulfur oxides, fly ash, and mercury. Solid waste ash from coal-fired boilers must also be removed, although some coal ash is recycled for building materials.

A coal plant is classified by its operating temperature and pressure. The three basic configurations are,

1. Sub-critical steam plants
2. Super-critical steam plants
3. Ultra-super-critical steam plants

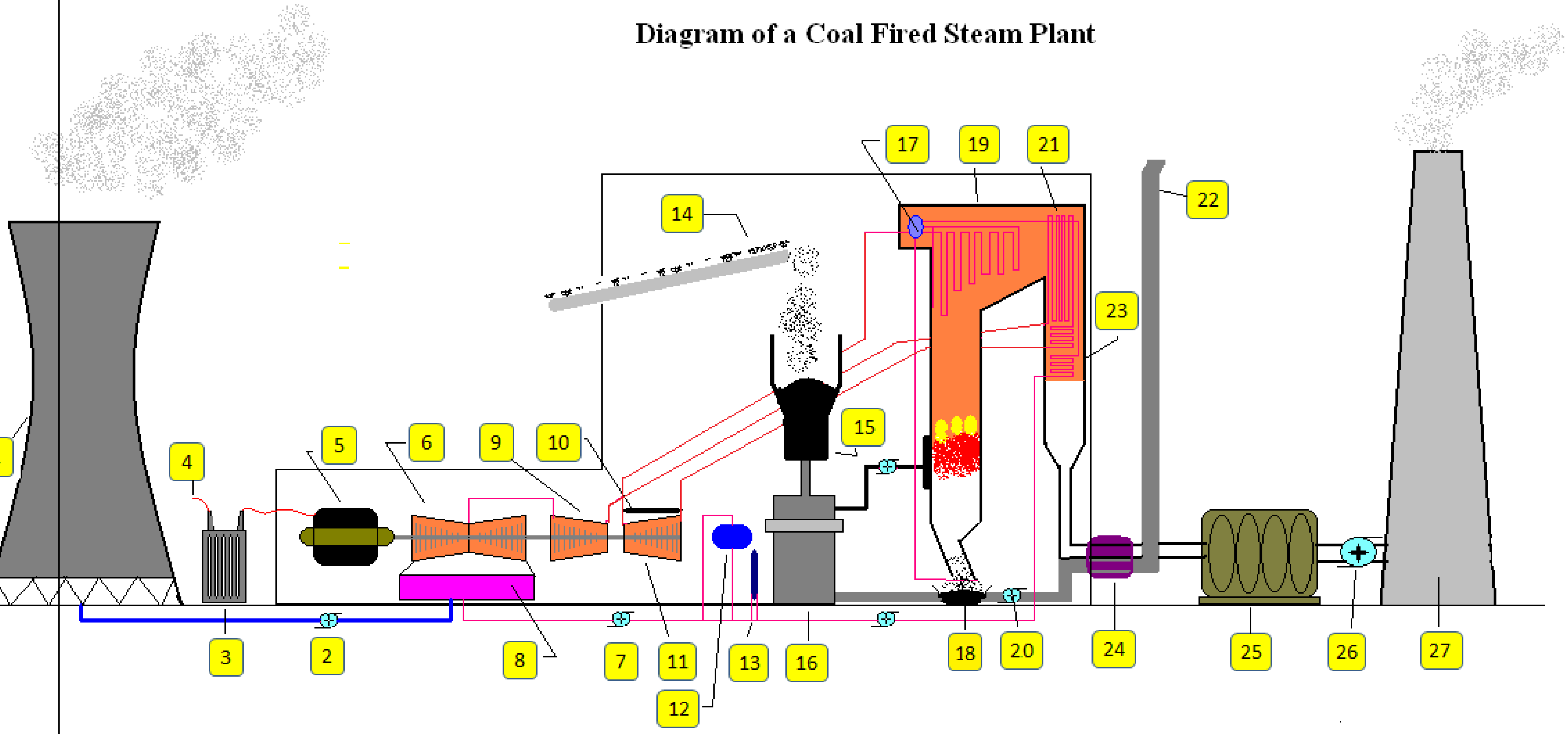
Early coal-fired steam plants heated water to a boil to produce steam to run the turbines. These plants, many which are still in operation today, are called *sub-critical* plants and operate at pressures of around 2,500 psi. At this pressure, as water is heated it will beginning boiling and then transition to steam. Sub-critical fossil fuel power plants can achieve efficiencies of 36–40%.

Modern coal plants are known as *Super-critical* plants and operate about the critical point for water, which is 374C and 3,212 psi. Above this temperature and pressure, there is no phase transition from water to steam, but only a gradual decrease in density. Super-critical designs have efficiencies in the low to mid 40% range. Since boiling does not occur it is not possible to remove impurities via steam separation. A supercritical steam plant utilizes the increased thermodynamic efficiency of operating at higher temperatures. These plants, also called once-through plants because boiler water does not circulate multiple times, require additional water purification steps to ensure that any impurities picked up during the cycle will be removed. This purification takes the form of high pressure ion exchange units called *condensate polishers* between the steam condenser and the feedwater heaters.

The newest form of coal-fired steam plants are called *ultra-super-critical* steam plants and operate at pressures of 4,400 psi and temperatures in excess of 600C. These units can reach efficiencies of 48%. Naturally the increase in efficiency reduces the amount of coal that must be burned to generate electricity, so these units have an immediate environmental benefit. These can also take advantage of lower BTU fuel such as Powder River Basin coal. Ultra-super-critical plants are made possible by advancements in metallurgy, such as the development of chrome and nickel-based super alloys that can withstand high-temperatures and high-pressures.

See Figure 4 on the next page for a diagram of a typical coal-fired power plant. This figure will be used to describe each of the major components of a coal-fired power plant. The description that follows explains the process from coal entering the facility to the generation of electricity.

Diagram of a Coal Fired Steam Plant



1. Cooling tower
2. Cooling water pump
3. Unit transformer
4. Transmission line
5. Electric generator
6. Low pressure turbine
7. Boiler feed pump
8. Condensor
9. Intermediate pressure turbine
10. Steam governor valve
11. High pressure turbine
12. De-aerator
13. Feed heater
14. Coal conveyor
15. Coal hopper
16. Pulverized fuel mill
17. Boiler drum
18. Ash hopper
19. Superheater
20. Forced draft fan
21. Reheater
22. Air intake
23. Economizer
24. Air preheater
25. Electrostatic Precipitator
26. Induced draft fan
27. Chimney Stack

Figure 4

Looking at Figure 4, let’s follow the energy path through the plant. The numbers in parenthesis match the numbers in the yellow boxes in Figure 4.

Coal is conveyed (14) from an external stack and ground to a very fine powder by large metal spheres in the pulverized fuel mill (16). There it is mixed with preheated air (24) driven by the forced draft fan (20).

The hot air-fuel mixture is forced at high pressure into the boiler where it rapidly ignites. Water of a high purity flows vertically up the tube-lined walls of the boiler, where it turns into steam, and is passed to the boiler drum, where steam is separated from any remaining water. The steam passes through a manifold in the roof of the drum into the pendant superheater (19) where its temperature and pressure increase rapidly to around 2,900 PSI and 570°C, sufficient to make the tube walls glow a dull red.

The steam is piped to the high-pressure turbine (11), the first of a three-stage turbine process. A steam governor valve (10) allows for both manual control of the turbine and automatic set point following. The steam is exhausted from the high-pressure turbine, and reduced in both pressure and temperature, and returned to the boiler reheater (21).

The reheated steam is then passed to the intermediate pressure turbine (9), and from there passed directly to the low pressure turbine set (6). The exiting steam, now a little above its boiling point, is brought into thermal contact with cold water (pumped in from the cooling tower) in the condensor (8), where it condenses rapidly back into water, creating near vacuum-like conditions inside the condensor chest.

The condensed water is then passed by a feed pump (7) through a deaerator (12), and pre-warmed, first in a feed heater (13) and then in the economizer (23), before being returned to the boiler drum.

The cooling water from the condensor is sprayed inside a cooling tower (1), creating a highly visible plume of water vapor, before being pumped back to the condensor (8) in cooling water cycle.

The three turbine sets are coupled on the same shaft as the three-phase electrical generator (5) which generates an intermediate level voltage (typically 20-25 kV). This is stepped up by a transformer (3) to a voltage more suitable for transmission (typically 250-500 kV) and is sent out onto the three-phase transmission system (4).

Exhaust gas from the boiler is drawn by the induced draft fan (26) through an electrostatic precipitator (25) and is then vented through the chimney stack (27).

Next, we will look at a few of the major components in a little more detail.

Fuel Transport and Delivery

Coal is delivered to the power plant by highway truck, rail, barge, or collier ship. Some plants are built near coal mines and coal is delivered by conveyors. A large coal train called a *unit train*, or *rake*, may be over a mile long, containing 100 cars with 100 tons of coal in each one, for a total load of 10,000 tons. A large plant that is at full load operation requires at least one coal delivery this size every day. Plants may get as many as three to five trains a day, especially in high demand seasons.

Photo courtesy DOE

A cargo ship carrying coal may hold 40,000 tons of coal and takes several days to unload. Some ships carry their own conveying equipment to unload their own bunkers; others depend on equipment at the plant. For transporting coal in calmer waters, such as rivers and lakes, flat-bottomed barges are often used.

The coal handling plant handles the coal from its receipt at the power plant to transporting it to boiler and storage in bunkers. It also processes the raw coal to make it suitable for boiler operation.

The coal handling plant involves receiving the coal from coal mines, weighing of coal, crushing it to required size and transferring it to various coal mill bunkers.

At the plant site, some or all of the following components may be found: Wagon tipplers, vibrating feeders, conveyor belts, coal crushers, trippers, electromagnetic separators, dust extraction systems, and gas extractors.

Wagon tipplers are the giant machines having gear boxes and motor assembly and are used to unload the coal wagons into coal hoppers quickly. *Vibrating feeders* are electromagnetic vibrating feeders or sometimes in the form of dragging chains which are provided below the coal hoppers. This equipment is used for controlled removal of coal from coal hoppers. *Conveyor belts* are the synthetic rubber belts which move on metallic rollers called idlers and are used for shifting of coal from one place to other places. *Coal crushers* receive the coal in the form of odd shaped lumps. These lumps are to be crushed to required size. These lumps are crushed by coal crushers. *Trippers* are the motorized or manually operated machines and are used for feeding the coal to different coal bunkers as per their requirement. *Electromagnetic separators* are used for removing of Iron and magnetic impurities from the coal. *Dust extraction systems* are provided in CHP for suppression of coal dust in coal handling plant. *Gas extractors* are provided at the bunker level to remove all types of poisonous and non poisonous gases from the working area.

Modern unloaders use rotary dump devices, which eliminate problems with coal freezing in bottom dump cars. The unloader includes a train positioner arm that pulls the entire train to position each car over a coal hopper. The dumper clamps an individual car against a platform that swivels the car upside down to dump the coal. Swiveling couplers enable the entire operation to occur while the cars are still coupled together. Unloading a unit train takes about three hours.

Shorter trains may use railcars with an *air-dump*, which relies on air pressure from the engine plus a *hot shoe* on each car. This "hot shoe" when it comes into contact with a *hot rail* at the unloading trestle, shoots an electric charge through the air dump apparatus and causes the doors on the bottom of the car to open, dumping the coal through the opening in the trestle. Unloading one of these trains takes anywhere from an hour to an hour and a half. Older unloaders may still use manually operated bottom-dump rail cars and a "shaker" attached to dump the coal.

The normal operating cycle of a coal handling plant involves bunkering, stacking, and reclaiming the coal. The normal *bunkering cycle* involves shifting the coal received from coal wagons directly to coal bunkers. The *stacking cycle* is when there is no coal requirement at coal bunkers the coal is received and stacked in the coal yard. When coal is removed from the stack for use it is called the *reclaiming cycle*.

Once the coal is needed at the plant it is prepared for use by crushing the rough coal to pieces less than two inches in size. The coal is then transported from the storage yard to in-plant storage silos by rubberized conveyor belts.

In plants that burn pulverized coal, silos feed coal pulverizers that take the larger 2-inch pieces, grind them to the consistency of powder, sort them, and mix them with primary combustion air which transports the coal to the furnace and preheats the coal to drive off excess moisture content.

In plants that do not burn pulverized coal, the larger pieces may be directly fed into the silos which then feed the cyclone burners, which is a specific kind of combustor that can efficiently burn larger pieces of fuel.

Routinely during the coal handling process, a sample of coal is randomly collected from each rake and detailed chemical analysis, calculation of calorific value is carried out to confirm the coal meets the contract specifications.

Boiler operation

The boiler in a typical steam plant is huge; typically a rectangular furnace about 50 feet on a side and 130 feet tall. Its walls are made of a web of high pressure steel tubes.

Pulverized coal is air-blown into the furnace from fuel nozzles at the four corners and it rapidly burns, forming a large fireball at the center. The thermal radiation of the fireball heats the water that circulates through the boiler tubes near the boiler perimeter. The water circulation rate in the boiler is three to four times the throughput and is typically driven by pumps. As the water in the boiler circulates it absorbs heat and changes into steam at 374C and 3,212 psi. It is separated from the water inside a drum at the top of the furnace. The saturated steam is introduced into superheat pendant tubes that hang in the hottest part of the combustion gases as they exit the furnace. Here the steam is superheated to prepare it for the turbine.

Steam turbine generator

A steam turbine uses a liquid that evaporates when heated and expands to produce work, such as turning a turbine. The working fluid most commonly used is water, though other liquids can also be used. The thermodynamic cycle for the steam turbine is the *Rankine cycle*. The cycle is the basis for conventional power generating stations and consists of a boiler that converts water to high pressure steam. The steam flows through the turbine to produce power. The steam exiting the turbine is condensed and returned to the boiler to repeat the process.

The Rankine cycle is a four-stage process. In the first stage, the working fluid is pumped into a boiler. While the fluid is in the boiler, an external heat source - in this case burning coal - superheats the fluid. The hot water vapor then expands to drive a turbine. Once past the turbine, the steam is condensed back into liquid and recycled back to the pump to start the cycle all over again. Pump, boiler, turbine, and condenser are the four parts of a standard steam engine and represent each phase of the Rankine cycle. The following figure is a schematic of a Rankine cycle system.

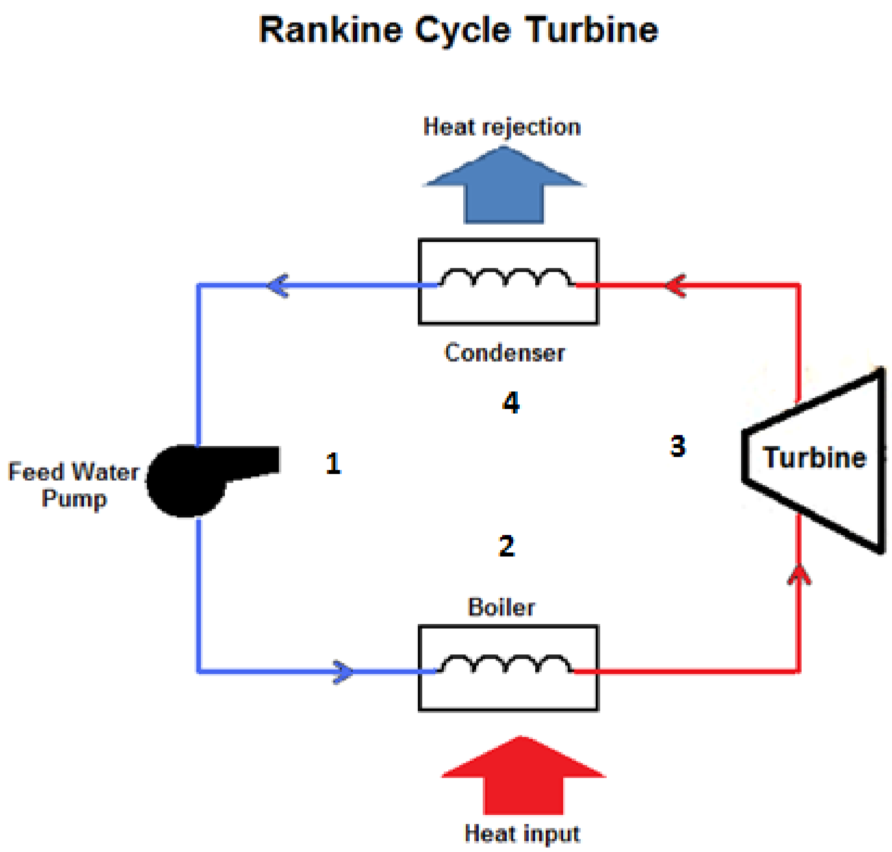


Figure 6

The four processes in the Rankine cycle each change the state of the working fluid. See the drawing in Figure 6 above.

In the first step the working fluid is pumped from low to high pressure, as the fluid is a liquid at this stage the pump requires little input energy.

Next, the high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor.

Passing through the boiler the dry saturated vapor expands through a turbine generating power output usually orders of magnitude greater than the power required by the pump. This decreases the temperature and pressure of the vapor and some condensation may occur.

In the final step, the wet vapor enters a condenser where it is cooled at a constant low pressure to become a saturated liquid. It is fully condensed to a liquid to minimize the work required by the pump.

In an ideal Rankine cycle, the compression by the pump and the expansion in the turbine would be completely reversible and there would be no losses in the conversion. Of course, in the real world the process does generate losses, which increases the power required by the pump and decreases the power generated by the turbine.

In comparison to combustion turbines where a significant fraction of the work generated by the turbine is required to drive the compressor, limiting net work output and efficiency, a Rankine cycle requires very little power for ancillary needs. By condensing the steam to water, the work required by the pump will only consume approximately 1% of the turbine power resulting in a much higher efficiency. As liquids are far less compressible they require only a fraction of the energy needed to compress a gas to the same pressure.

The efficiency of a Rankine cycle is usually limited by the working fluid. Without the pressure going super critical the operating temperature range is quite small; turbine entry temperature is typically 565C and condenser temperatures are around 30C. This gives a theoretical efficiency of around 63% compared with an actual efficiency of 42% for a modern coal fired power plant.

The working fluid in a Rankine cycle follows a closed loop and is re-used constantly. The efficiency of the steam turbine will be limited by water droplet formation. As the water condenses, water droplets hit the turbine blades at high speed causing pitting and erosion, gradually decreasing the efficiency of the turbine. The easiest way to overcome this problem is by superheating the steam.

Two main variations of the basic Rankine cycle: Rankine cycle with reheat and Regenerative Rankine cycles.

A *Rankine cycle with reheat* uses two turbines in series. The first accepts vapor from the boiler at high pressure. After the vapor has passed through the first turbine, it re-enters the boiler and is reheated before passing through a second, lower pressure turbine. This prevents the vapor from condensing during its expansion which can seriously damage the turbine blades, and improves the efficiency of the cycle.

The other variation is the *regenerative Rankine cycle*. With this process, the working fluid is heated by steam tapped from the hot portion of the cycle after emerging from the condenser. This increases the average temperature of heat addition which in turn increases the thermodynamic efficiency of the cycle.

A steam turbine consists of a stationary set of blades (called nozzles) and a moving set of adjacent blades (called buckets or rotor blades) installed within a casing. The two sets of blades work together such that the steam turns the shaft of the turbine and the connected load. A steam turbine converts pressure energy into velocity energy as it passes through the blades.

The primary type of turbine used for central power generation is the *condensing turbine*. Steam exhausts from the turbine at sub-atmospheric pressures, maximizing the heat extracted from the steam to produce useful work. The turbine generator consists of a series steam turbines interconnected to each other and a generator on a common shaft. There is a high pressure turbine at one end, followed by an intermediate pressure turbine, two low pressure turbines, and the generator. As steam moves through the system and loses pressure and thermal energy it expands in volume, requiring increasing diameter and longer blades at each succeeding stage to extract the remaining energy. The entire rotating mass may be over 200 tons and 100 feet long. It is so heavy that it must be kept turning slowly even when shut down so that the shaft will not bow even slightly and become unbalanced. This is so important that it is one of only five functions of blackout emergency power batteries on site. Other functions are emergency lighting, communication, station alarms and turbo-generator lube oil.

Superheated steam from the boiler is delivered through piping to the high pressure turbine where it falls in pressure to 600 psi and to 320C through the stage. It exits cold reheat lines and passes back into the boiler where the steam is reheated in special reheat pendant tubes back to 500C.

The hot reheat steam is conducted to the intermediate pressure turbine where it falls in both temperature and pressure and exits directly to the long-bladed low pressure turbines and finally exits to the condenser.

To maximize turbine efficiency the steam is expanded, generating work, in a number of stages. These stages are characterized by how the energy is extracted from them and are known as either impulse or reaction turbines (See Figure 7). Most steam turbines use a mixture of the reaction and impulse designs: each stage behaves as either one or the other, but the overall turbine uses both. Typically, higher pressure sections are impulse type and lower pressure stages are reaction type.

An *impulse turbine* has fixed nozzles that orient the steam flow into high speed jets. These jets contain significant kinetic energy, which the rotor blades, shaped like buckets, convert into shaft rotation as the steam jet changes direction. A pressure drop occurs across only the stationary blades, with a net increase in steam velocity across the stage.

As the steam flows through the nozzle its pressure falls from inlet pressure to the exit pressure (atmospheric pressure, or more usually, the condenser vacuum). Due to this higher ratio of expansion of steam in the nozzle the steam leaves the nozzle with a very high velocity. The steam leaving the moving blades has a large portion of the maximum velocity of the steam when leaving the nozzle.

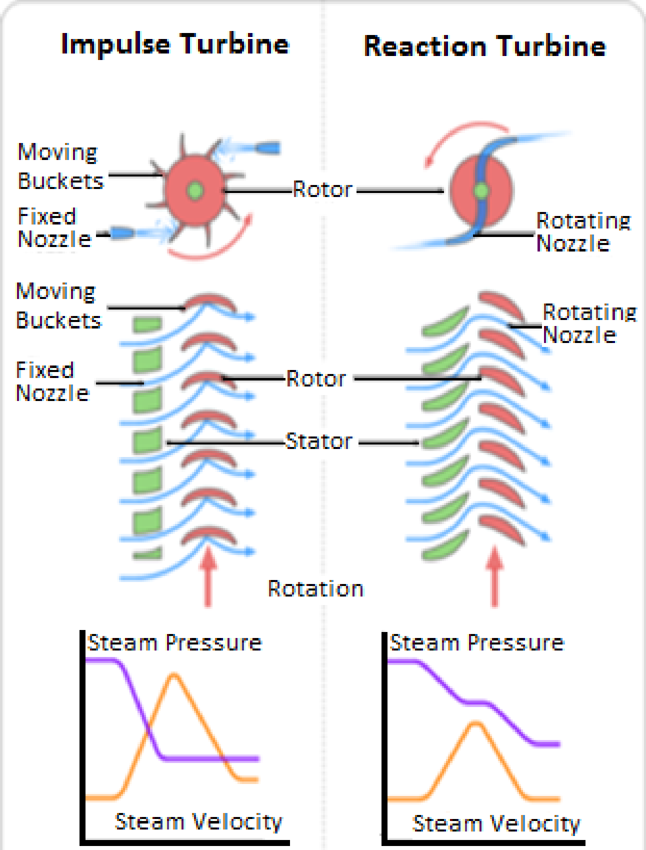


Figure 7

In *the reaction turbine*, the rotor blades themselves are arranged to form convergent nozzles. This type of turbine makes use of the reaction force produced as the steam accelerates through the nozzles formed by the rotor. Steam is directed onto the rotor by the fixed vanes of the stator. It leaves the stator as a jet that fills the entire circumference of the rotor. The steam then changes direction and increases its speed relative to the speed of the blades. A pressure drop occurs across both the stator and the rotor, with steam accelerating through the stator and decelerating through the rotor, with no net change in steam velocity across the stage but with a decrease in both pressure and temperature, reflecting the work performed in the driving of the rotor.

Feed water heating and de-aeration

The feed water used in the steam boiler is a means of transferring heat energy from the burning fuel to the mechanical energy of the spinning steam turbine. The total feed water consists of re-circulated condensate water and purified makeup water. Because the metallic materials it contacts are subject to corrosion at high temperatures and pressures, the makeup water is highly purified before use. A system of water softeners and ion exchange de-mineralizers produces water so pure that it coincidentally becomes an electrical insulator. The make-up water in a typical plant amounts to perhaps 20 gallons per minute to offset the small losses from steam leaks in the system.

The feedwater cycle begins with condensate water being pumped out of the condenser after traveling through the steam turbines. The condensate flow rate at full load may be 6,000 gallons per minute or more.

The water flows through a series intermediate feedwater heaters, heated up at each point with steam extracted from an appropriate duct on the turbines and gaining temperature at each stage.

Typically, the condensate plus the makeup water then flows through a deaerator that removes dissolved air from the water, further purifying and reducing its corrosivity. The water may be dosed following this point with hydrazine, a chemical that removes the remaining oxygen in the water. It is also dosed with pH control agents such as ammonia to keep the residual acidity low and thus non-corrosive.

Figure 5 shows a typical boiler feedwater de-aerator.

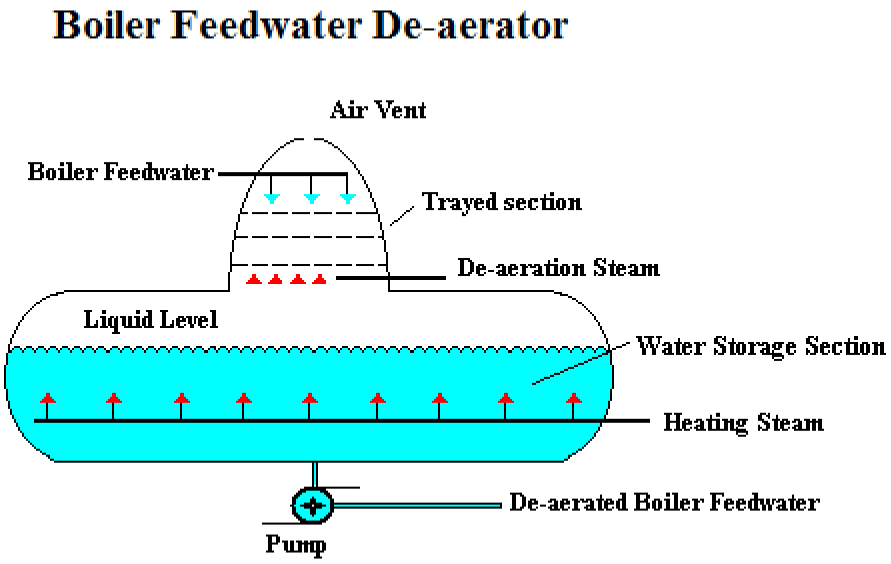


Figure 5

Electric Generator

Connected to the steam generator is an electric generator. The generator contains a stationary stator and a spinning rotor, each containing miles of heavy copper conductor. The rotor spins in a sealed chamber cooled with hydrogen gas, selected because it has the highest known heat transfer coefficient of any gas and for its low viscosity which reduces windage losses. This system requires special handling during startup, with air in the chamber first displaced by carbon dioxide before filling with hydrogen. This ensures that the highly explosive hydrogen–oxygen environment is not created.

Steam condensing

The *condenser* condenses the steam from the exhaust of the turbine into liquid to allow it to be pumped. If the condenser can be made cooler, the pressure of the exhaust steam is reduced and efficiency of the cycle increases. The condenser is usually a shell and tube heat exchanger commonly referred to as a *surface condenser*. Cooling water circulates through the tubes in the condenser's shell and the low pressure exhaust steam is condensed by flowing over the tubes as shown in the adjacent diagram. The tubing is designed to reduce the exhaust pressure, avoid sub-cooling the condensate and provide adequate air extraction. Typically the cooling water causes the steam to condense at a temperature of about 30C and that creates a vacuum relative to atmospheric pressure. The large decrease in volume that occurs when water vapor condenses to liquid creates the low vacuum that helps pull steam through and increase the efficiency of the turbines. The limiting factor is the temperature of the cooling water and that, in turn, is limited by the prevailing average climatic conditions at the power plant's location.

From the bottom of the condenser, powerful condensate pumps recycle the condensed steam – or water - back to the water/steam cycle.

The heat absorbed by the circulating cooling water in the condenser tubes must also be removed to maintain the ability of the water to cool as it circulates. This is done by pumping the warm water from the condenser through either natural draft, forced draft or induced draft cooling towers that reduce the temperature of the water by evaporation, expelling waste heat to the atmosphere.

The condenser tubes are made of brass or stainless steel to resist corrosion from either side. Nevertheless they may become internally fouled during operation by bacteria or algae in the cooling water or by mineral scaling, all of which inhibit heat transfer and reduce thermodynamic efficiency. Many plants include an automatic cleaning system that circulates sponge rubber balls through the tubes to scrub them clean without the need to take the system off-line.

The cooling water used to condense the steam in the condenser returns to its source without having been changed other than having been warmed. If the water returns to a local water body (rather than a circulating cooling tower), it is tempered with cool raw water to prevent thermal shock when discharged into that body of water.

Another form of condensing system is the air-cooled condenser. The process is similar to that of a radiator and fan. Exhaust heat from the low pressure section of a steam turbine runs through the condensing tubes, the tubes are usually finned and ambient air is pushed through the fins with the help of a large fan. The steam condenses to water to be reused in the water-steam cycle. Air-cooled condensers typically operate at a higher temperature than water cooled versions. While saving water, the efficiency of the cycle is reduced, which results in more carbon dioxide per megawatt of electricity.

Cooling tower

Cooling towers are heat removal devices used to transfer process waste heat to the atmosphere. Cooling towers may either use the evaporation of water to remove process heat and cool the working fluid to near the wet-bulb air temperature or rely solely on air to cool the working fluid to near the dry-bulb air temperature.

The primary use of large cooling towers is to remove the heat absorbed in the circulating cooling water systems used in power plants.

The circulation rate of cooling water in a typical coal-fired power plant with a cooling tower amounts to about 315,000 gallons per minute and the circulating water requires a supply water make-up rate of perhaps 5 percent. If that same plant had no cooling tower and used once-through cooling water, it would require over 400,000 gallons per hour and that amount of water would have to be continuously returned to the ocean, lake or river from which it was obtained and continuously re-supplied to the plant. Furthermore, discharging large amounts of hot water may raise the temperature of the receiving river or lake to an unacceptable level for the local ecosystem. Elevated water temperatures can kill fish and other aquatic organisms. A cooling tower serves to dissipate the heat into the atmosphere instead and wind and air diffusion spreads the heat over a much larger area than hot water can distribute heat in a body of water. Some coal-fired power plants located in coastal areas do make use of once-through ocean water. But even there, the offshore discharge water outlet requires very careful design to avoid environmental problems.

With respect to the heat transfer mechanism employed, the main types are:

- Wet cooling towers or simply cooling towers operate on the principle of evaporation. The working fluid and the evaporated fluid (usually H_2O) are one and the same.
- Dry coolers operate by heat transfer through a surface that separates the working fluid from ambient air, such as in a heat exchanger, utilizing convective heat transfer. They do not use evaporation.

In a wet cooling tower, the warm water can be cooled to a temperature lower than the ambient air dry-bulb temperature, if the air is relatively dry. As ambient air is drawn past a flow of water, evaporation occurs. Evaporation results in saturated air conditions, lowering the temperature of the water to the wet bulb air temperature, which is lower than the ambient dry bulb air temperature, the difference determined by the humidity of the ambient air.

Steam plants use a natural draft process to draw air through the tower. Natural draft utilizes buoyancy via a tall chimney. Warm, moist air naturally rises due to the density differential to the dry, cooler outside air. Warm moist air is less dense than drier air at the same pressure. This moist air buoyancy produces a current of air through the tower.

Hyperboloid cooling towers have become the design standard for all natural-draft cooling towers because of their structural strength and minimum usage of material. The hyperboloid shape also aids in accelerating the upward convective air flow, improving cooling efficiency. They are popularly associated with nuclear power plants. However, this association is misleading, as the same kind of cooling towers are often used at large coal-fired power plants as well.

Under certain ambient conditions, plumes of water vapor (fog) can be seen rising out of the discharge from a cooling tower (, and can be mistaken as smoke from a fire. If the outdoor air is at or near saturation, and the tower adds more water to the air, saturated air with liquid water droplets can be discharged—what is seen as fog. This phenomenon typically occurs on cool, humid days, but is rare in many climates.

Stack gas path and cleanup

As the combustion flue gas exits the boiler it is routed through a rotating flat basket of metal mesh which picks up heat and returns it to incoming fresh air as the basket rotates, This is called the *air preheater*. The gas exiting the boiler is laden with fly ash, which are tiny spherical ash particles. The flue gas contains nitrogen along with combustion products carbon dioxide, sulfur dioxide, and nitrogen oxides. The fly ash is removed by fabric bag filters or electrostatic precipitators. Once removed, the fly ash byproduct can sometimes be used in the manufacturing of concrete. This cleaning up of flue gases, however, only occurs in plants that are fitted with the appropriate technology. Still, the majority of coal fired power plants in the world do not have these facilities.

The sulfur and nitrogen oxide pollutants are removed by stack gas scrubbers which use a pulverized limestone or other alkaline wet slurry to remove those pollutants from the exit stack gas. Other devices use catalysts to remove Nitrous Oxide compounds from the flue gas stream. The gas travelling up the flue gas stack may by this time have dropped to about 50C. A typical flue gas stack may be 500 feet tall to disperse the remaining flue gas components in the atmosphere.

Chapter 3
Environmental Issues

Burning coal to create electricity in coal-fired steam plants creates a number of potentially adverse environmental effects. These effects include:

- Some types of coal mining cause severe erosion, resulting in the leaching of toxic chemicals into nearby streams and aquifers, and destroys habitants.
- About two-thirds of sulfur dioxide, one-third of carbon dioxide emissions and one quarter of the nitrogen oxide emissions in the U.S. are produced by coal burning.
- Coal burning also results in the emission of fine particles matter into the atmosphere. Nitrogen oxide and fine airborne particles exacerbate asthma, reduce lung function and cause respiratory diseases for thousands of people.
- Smog formed by nitrogen oxide and reactive organic gases cause crop, forest and property damage. Sulfur dioxide and nitrogen oxides both combine with water in the atmosphere to create acid rain. Acid rain acidifies the soils and water killing off plants, fish, and the animals that depend on them.
- Global warming is partially caused by carbon dioxide emissions and is responsible for at least half of the warming.

Let’s look at a few of the environmental impacts of the coal burning process.

Acid Rain

The combustion of coal contributes the most to acid rain and air pollution, and has been connected with global warming. Due to the chemical composition of coal there are difficulties in removing impurities from the solid fuel prior to its combustion. Modern day coal power plants pollute very little due to new technologies in "scrubber" designs that filter the exhaust air in smoke stacks. Today, the only pollution caused from coal-fired power plants comes from the emission of gases—carbon dioxide, nitrogen oxides, and sulfur dioxide into the air. Acid rain is caused by the emission of nitrogen oxides and sulfur dioxide into the air. These may be only mildly acidic, yet when they react with the atmosphere, they create acidic compounds (such as sulfurous acid, nitric acid and sulfuric acid) that fall as rain, hence the term *acid rain*. In the US strict emission laws and decline in heavy industries have reduced the environmental hazards associated with this problem, leading to lower emissions after their peak in 1960s.

Carbon dioxide

Electricity generation using carbon based fuels is responsible for a large fraction of carbon dioxide (CO_2) emissions worldwide and for 41% of U.S. man-made carbon dioxide emissions. Of fossil fuels, coal combustion in thermal power stations result in the greatest amount of carbon dioxide emissions per unit of electricity generated – 2,249 lbs/MWh – while oil produces less at1,672 lb/MWh and natural gas produces the least at 1,135 lb/MWh.

Many believe that carbon dioxide is a greenhouse gas and that increased quantities within the atmosphere will lead to higher average temperatures on a global scale (global warming).

Emissions may be reduced through more efficient and higher combustion temperature and through more efficient production of electricity within the cycle. Carbon capture and storage (CCS) of emissions from coal fired power stations is another alternative but the technology is still being developed and will increase the cost of fossil fuel-based production of electricity.

Particulate matter

Another problem related to coal combustion is the emission of particulates that have a serious impact on public health. Power plants remove particulate from the flue gas with the use of a bag house or electrostatic precipitator.

Particulate matter from coal-fired plants can be harmful and have negative health impacts. Studies have shown that exposure to particulate matter is related to an increase of respiratory and cardiac mortality. Particulate matter can irritate small airways in the lungs, which can lead to increased problems with asthma, chronic bronchitis, airway obstruction, and gas exchange. There are different types of particulate matter, depending on the chemical composition and size. The dominant form of particulate matter from coal-fired plants is coal fly ash, but secondary sulfate and nitrate also comprise a major portion of the particulate matter from coal-fired plants. Coal fly ash is what remains after the coal has been combusted, so it consists of the incombustible materials that are found in the coal.

The size and chemical composition of these particles affects the impacts on human health.

Currently coarse and fine particles are regulated, but ultrafine particles are currently unregulated, yet they may pose dangers. Unfortunately much is still unknown as to which kinds of particulate matter pose the most harm, which makes it difficult to regulate particulate matter.

There are several methods to help to reduce the particulate matter emissions from coal-fired plants. Roughly 80% of the ash falls into an ash hopper, but the rest of the ash then gets carried into the atmosphere to become coal-fly ash. Methods of reducing these emissions of particulate matter include: a baghouse, an electrostatic precipitator, and a cyclone collector.

The *baghouse* has a fine filter that collects the ash particles, *electrostatic precipitators* use an electric field to trap ash particles on high-voltage plates, and *cyclone collectors* use centrifugal force to trap particles to the walls.

Mountain Top Removal

Environmentalist claim that mountaintop mining has serious environmental impacts, including loss of biodiversity, and adverse human health impacts which result from contact with affected streams or exposure to airborne toxins and dust.

Mountain top removal mining (MTR), also known as mountaintop mining is a form of surface mining that involves the mining of the summit ridge of a mountain. Entire coal seams are removed from the top of a mountain, hill or ridge by removing the *overburden* (soil, lying above the economically desired resource). After the coal is extracted, the removed material is put back onto the ridge to approximate the mountain's original contours. Any overburden that cannot be put back onto the ridge top is moved into neighboring valleys. Mountaintop removal is most closely associated with coal mining in the Appalachian Mountains in the eastern United States.

Environmentalist claim that mountaintop mining has serious environmental impacts, including loss of biodiversity, and adverse human health impacts which result from contact with affected streams or exposure to airborne toxins and dust.

The MTR process involves the removal of coal seams by first fully removing the overburden lying atop them, exposing the seams from above. This method differs from more traditional underground mining, where typically a narrow shaft is dug which allows miners to collect seams using various underground methods, while leaving the vast majority of the overburden undisturbed. The overburden waste resulting from MTR is either placed back on the ridge, attempting to reflect the approximate original contour of the mountain, and/or it is moved into neighboring valleys.

The process involves blasting to remove overburden to expose underlying coal seams. Excess rock and soil laden with mining byproducts are often moved into nearby valleys, in what are called "holler fills" or "valley fills."

Mountaintop removal has been practiced since the 1960s. Increased demand for coal in the United States, sparked by the petroleum crises in the 1970’s, created incentives for a more economical form of coal mining than the traditional underground mining methods involving hundreds of workers, triggering the first widespread use of MTR. Its prevalence expanded further in the 1990s to retrieve relatively low-sulfur coal, a cleaner-burning form, which became desirable as a result of amendments to the U.S. Clean Air Act that tightened emissions limits on high-sulfur coal processing.

The coal industry asserts that surface mining techniques, such as mountaintop removal, are safer for miners than sending them underground.

Proponents argue that in certain geologic areas, MTR and similar forms of surface mining allow the only access to thin seams of coal that traditional underground mining would not be able to mine. MTR is sometimes the most cost-effective method of extracting coal.

Critics contend that MTR is a destructive and unsustainable practice that benefits a small number of corporations at the expense of local communities and the environment. Though the main issue has been over the physical alteration of the landscape, opponents to the practice have also criticized MTR for the damage done to the environment by massive transport trucks, and the environmental damage done by the burning of coal for power. Blasting at MTR sites also expels dust and fly-rock into the air, which can disturb or settle onto private property nearby. This dust may contain sulfur compounds, which corrodes structures and is a health hazard.

Advocates of MTR claim that once the areas are reclaimed - as mandated by law - the area can provide flat land suitable for many uses in a region where flat land is at a premium. They also maintain that the new growth on reclaimed mountaintop mined areas is better suited to support populations of game animals.

Carbon Sequestration

There are generally three ways to manage carbon emissions,

1. Reduce the need for fossil fuel combustion through increased energy efficiency.
2. Use alternative low-carbon and carbon-free fuels and technologies such as nuclear power and renewable sources.

3. Capture and securely store carbon emitted from the fossil fuel combustion, which is known as carbon sequestration.

The purpose of *carbon sequestration* is to keep carbon emissions from reaching the atmosphere by capturing them, isolating them, and diverting them to secure storage. Any viable system for sequestering carbon must be safe, environmentally benign, effective, and economical. In addition, it must be acceptable to the public.

Several available technologies are used to separate and capture CO_2 from fossil-fueled power plant flue gases. The use of existing technology for removing CO_2 is projected to raise the cost of producing electrical power from coal-fired power plants. Although CO_2 is separated routinely, dramatic improvements are necessary to make the process economical. Techniques are needed to transform the captured CO_2 into materials that can be economically and safely transported and sequestered for a long time.

There are numerous options for the separation and capture of CO_2, and many of these are commercially available. However, none has been applied at the scale required as part of a CO_2 emissions mitigation strategy. Many issues remain regarding the ability to separate and capture CO_2 from sources on the scale required, and to meet the cost, safety, and environmental requirements for separation and capture. The three most promising methods of carbon storage include:

- Ocean sequestration,
- Terrestrial ecosystem sequestration, and
- Geologic formation sequestration.

There are many technological issues to resolve before carbon sequestration will be a viable environmental option.

Geologic Sequestration

Three principal types of geologic formations are widespread in the United States and have the potential for sequestering large amounts of CO_2. They are active and uneconomical oil and gas reservoirs, aqueous formations, and deep coal formations. Presently about 70 oil fields worldwide use injected CO_2 for enhanced oil recovery. The United States has sufficient capacity, diversity, and broad geographic distribution of potential reservoirs to use geologic sequestration in the near term. The primary uncertainty is the effectiveness of storing CO_2 in geological formations - how easily CO_2 can be injected and how long it will remain. Many important issues must be addressed to reduce costs, ensure safety, and gain public acceptance.

Geologic formations, such as oil fields, coal beds, and aquifers, are likely to provide the first large scale opportunity for concentrated sequestration of CO_2. Developers of technologies for sequestration of CO_2 in geologic formations can draw from related experience gained over nearly a century of oil and gas production, groundwater resource management, and, more recently, natural gas storage and groundwater remediation. In some cases, sequestration may even be accompanied by economic benefits such as enhanced oil recovery, enhanced methane production from coal beds, enhanced production of natural gas from depleted fields, and improved natural gas storage efficiency through the use of CO_2 as a "cushion gas" to displace methane from the reservoir.

CO_2 can be sequestered in geologic formations by three principal mechanisms. First, CO_2 can be trapped as a gas or supercritical fluid under a low-permeability caprock, similar to the way that natural gas is trapped in gas reservoirs or stored in aquifers. This mechanism, commonly called *hydrodynamic trapping*, will likely be the most important for sequestration. Finding better methods to increase the fraction of space occupied by trapped gas will enable maximum use of the sequestration capacity of a geologic formation.

Second, CO_2 can dissolve into the fluid phase. This mechanism of dissolving the gas in a liquid such as petroleum is called solubility trapping. In oil reservoirs, dissolved CO_2 lowers the viscosity of the residual oil so it swells and flows more readily, providing the basis for one of the more common oil recovery techniques. The relative importance of solubility trapping depends on a large number of factors, such as the *sweep efficiency* of CO_2 injection, the formation of fingers (preferred flow paths), and the effects of formation heterogeneity. Efficient solubility trapping will reduce the likelihood that CO_2 gas will quickly return to the atmosphere.

Finally, CO_2 can react either directly or indirectly with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix. In most geologic formations, formation of calcium, magnesium, and iron carbonates is expected to be the primary mineral trapping processes. However, precipitation of these stable mineral phases is a relatively slow process with poorly understood kinetics. In coal formations, trapping is achieved by preferential adsorption of CO_2. Developing methods for increasing the rate and capacity for mineral trapping will create stable repositories of carbon that are unlikely to return to the biosphere and will decrease unexpected leakage of CO_2 to the surface.

To sequester CO_2 produced from the combustion of fossil fuels to generate electricity, CO_2 needs to be separated from the waste stream to a purity of at least 90%. CO_2 is then transported as a supercritical fluid by pipeline to the nearest geologic formation suitable for sequestration. The cost for transportation will likely be significant.

Ocean Sequestration

The ocean represents a large potential storage location for carbon dioxide. One solution is to inject a relatively pure CO_2 stream that has been generated by a power plant directly into the deep ocean. The injected CO_2 may become trapped in ocean sediments or ice-like solids, called hydrates. Another option is to increase the net oceanic uptake from the atmosphere by enhancing the ocean ability to absorb CO_2 with iron fertilization. Active experiments are already under way in iron fertilization and other tests of enhanced marine biological sequestration, as well as deep CO_2 injection. These approaches will require better understanding of marine ecosystems to enhance the effectiveness of applications and avoid undesirable consequences.

The ocean represents a large potential sink for sequestration of CO_2 emissions, although the long-term effectiveness and potential side effects of using the oceans in this way are unknown. There are two primary methods of enhancing ocean sequestration,

- The direct injection of CO_2
- Enhancement of the natural ocean uptake from the atmosphere

For a given option the tradeoffs among cost, long-term effectiveness, and changes to the ocean ecosystem are discussed.

On average, the ocean is about 13,000 feet deep and contains 40,000 GtC of CO_2. It is made up of a surface layer (nominally 300 feet thick), a thermocline (down to about 3,000 feet deep) that is stably stratified, and the deep ocean below 3,000 feet. Its waters circulate between surface and deep layers on varying time scales from 250 years in the Atlantic Ocean to 1,000 years for parts of the Pacific Ocean. The amount of carbon that would cause a doubling of the atmospheric concentration would change the deep ocean concentration by less than 2%.

On a time scale of 1,000 years, about 85% of today’s emissions of CO_2 will be transferred to the ocean. The strategy with ocean sequestration is to attempt to speed up this process to reduce both peak atmospheric CO_2 concentrations and their rate of increase.

Terrestrial Sequestration

Terrestrial ecosystems, which are made up of vegetation and soils containing microbial and invertebrate communities, sequester CO_2 directly from the atmosphere. The terrestrial ecosystem is essentially a huge natural biological scrubber for CO_2 from all fossil fuel emissions sources, such as automobiles, power plants, and industrial facilities. The ability of the ecosystem to sequester carbon can be significantly increased over the next few years to provide a critical “bridging technology” while other carbon management options are developed. The potential for terrestrial ecosystems to remove and sequester more carbon from the atmosphere could be increased by, for example, improving agricultural cultivation practices to reduce oxidation of soil carbon and enhancing soil texture to trap more carbon, and protecting wetlands.

The terrestrial biosphere is another potential avenue for sequestering carbon. The aim of developing enhanced carbon sequestration in the biosphere is to enable a rapid gain in withdrawal of CO_2 from the atmosphere over the next 50 years in order to allow time for implementation of other technological advances that will help mitigate CO_2 emissions.

Carbon sequestration in terrestrial ecosystems is either the net removal of CO_2 from the atmosphere or the prevention of CO_2 net emissions from terrestrial ecosystems into the atmosphere. Carbon sequestration may be accomplished by increasing photosynthetic carbon fixation, reducing decomposition of organic matter, reversing land use changes that contribute to global emissions, and creating energy offsets through the use of biomass for fuels or beneficial products. The latter two methods may be viewed more appropriately as carbon management strategies.

The terrestrial biosphere is estimated to sequester large amounts of carbon, on the order of two GtC/year. There are two fundamental approaches to sequestering carbon in terrestrial ecosystems: protection of ecosystems that store carbon so that sequestration can be maintained or increased and manipulation of ecosystems to increase carbon sequestration beyond current conditions. In this section, we will review the inventories of carbon in terrestrial ecosystems and the roles of the biosphere in the global sequestration process and then estimate the potential for carbon sequestration in each of them.

Carbon sequestration in terrestrial ecosystems will provide significant near-term benefits with the potential for even more major contributions in the long-term. There are many ancillary positive benefits from carbon sequestration in terrestrial ecosystems, which are already a major biological scrubber for CO_2. The potential for carbon sequestration could be large for terrestrial ecosystems (5–10 GtC/year). However, this value is speculative, and research is needed to evaluate this potential and its implications for ecosystems.

Summary

Coal-fired steam plants have been a cornerstone of electric power generation for over 100 years and will continue to be a major fuel source for many years to come. At the current burn rates known coal reserves will last for centuries.

Coal has significant environmental and societal issues. Improving efficiencies in coal-fired power plant operation as well as improved environmental controls may help coal to remain a viable fuel source. If the promise of carbon sequestration comes to pass, then coal-fired steam plants may remain as one of the lowest cost generation sources for several hundred years.

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