Electricity and Power Plants

Overview

Electricity is a flow of electrical charges through a conductor, such as a wire made of copper or aluminum. When those charges reach a destination, they can be converted into other forms of energy, such as light, heat, sound, or movement. The word comes from the Greek word for amber, a fossilized tree resin, and was first used by English scientist William Gilbert in 1600. This was 1000 years after Greek scientist Thales of Miletos reported that rubbing amber with fur imparted an ability to levitate feathers and other light objects. Thales opined that rubbing imparted the property of magnetism. We now believe rubbing imparts static electricity.

Electrical power plants (also called power stations, generating stations, or generating facilities) produce electricity by converting other forms of energy. **Photoelectric** power plants convert sunlight directly into electricity. **Fuel cells and batteries** use chemical reactions to produce electricity directly. **Ocean thermal** power plants exploit the difference in temperature between surface water and deep water to directly generate electricity. **Piezoelectric** power plants produce electricity directly by stressing crystals. Other generating technologies produce electricity indirectly, by using a source of thermal or kinetic energy to spin a generator, which is a device that moves an electrical conductor through a magnetic field and thereby produces electrical charges in the conductor. **Wind** machines use the kinetic energy in wind to spin turbine blades which are connected through a gearbox to a generator. **Hydroelectric** power stations pass flowing water through turbines, which are connected to generators. **Geothermal** power plants extract steam from the earth and allow it to expand while it passes through turbines, which are connected to generators. **Nuclear** power plants use the heat produced by radioactive decay to make steam, which is expanded through a turbine, which drives a generator. **Solar thermal** power plants use sunlight to generate the steam. Other **steam-cycle** power plants use the heat released by combustion of coal, oil, natural gas, oil shale, wood, and other fuels to make steam, which drives turbines and generators. **Combined cycle** power plants first use the heat of combustion of liquid fuels or gaseous fuels to spin a turbine generator (a jet engine integrated with a generator) and then produce steam with the heat that remains in the combustion gases. That steam drives turbines and generators. **Integrated gasification combined cycle** power plants produce gaseous fuel by reacting a solid fuel (usually coal) with oxygen (in pure form or in air) and burn that fuel in a turbine generator. The residual heat in the gases leaving the turbine generator produces steam, which drives another turbine, which spins a generator.

On the 2008 EMFI trip, we visited two very different types of power plants. **Morrow Point,** a hydroelectric power plant located near Cimarron, Colorado, produces electricity with falling water from the Gunnison River. It is operated by the U.S. Bureau of Reclamation, an agency of the U.S. Department of the Interior. With an installed capacity of 173 megawatts (MW), Morrow Point is relatively small as hydro plants go.[1] However it serves a valuable role as a peaking plant, because its two generators can be turned on or off quickly, enabling the regional grid to follow surges in electricity demand.

Nucla Station is a coal-fired steam-cycle power plant located near the town of Nucla, Colorado. Nucla Station is owned and operated by Tri-State Generation & Transmission Association, Inc. It is a base-load facility, meaning it is intended to operate more or less continuously at the same output, more or less.

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[1] The largest hydroelectric plant is Itaipu, on the Parana River at the border between Brazil and Paraguay. It has a capacity of 14,750 MW. Grand Coulee (6495 MW) is the largest in the United States. It is located on the Columbia River in the state of Washington.

With a rated output of 100 MW, Nucla Station is also relatively small[2]. However Nucla uses an unusual and potentially very important technology – circulating fluidized bed combustion.

Pulverized Coal Generation Technology

Most electricity in the United States is generated by fossil-fueled steam-cycle power plants. Methods for producing ("raising") steam have evolved over the centuries, from heating pots of water over piles of burning logs, to confining the water in heat exchangers (bundles of tubes exposed to the hot combustion gases), to traveling grate boilers in which lumps of coal move as they burn, to the complex technologies used in modern power plants. These use combinations of heat exchange devices (preheaters, waterwall boilers, superheaters, recuperators) to extract the maximum amount of energy from the burning fuel.

In a modern coal-fired power plant (Figs. 1 and 2), the coal is first pulverized to increase the rate at which it burns. This coal dust is then blown into a boiler – a large and very hot room made of metal and lined with firebrick and other refractory materials. As the coal burns, its chemical energy is converted into heat and light. The heat passes through the walls of the boiler and is absorbed by water moving through metal tubes. The water boils and is converted into steam. This "low temperature" steam travels up to a heat exchanger called a superheater, where it is further heated by the combustion gases to temperatures in excess of 1000 ^{o}F. The steam is then sent through a steam turbine[3] where it expands and spins a series of fan-like blades. This converts the heat energy of the steam into mechanical energy. The blades are mounted on a shaft, which also rotates, and which is connected to the shaft of a generator. Coils of wire mounted around the shaft move very rapidly through a magnetic field created by magnets mounted on the sides of the generator.[4] Moving the conducting wires through the magnetic field generates a voltage across the ends of the conductor, causing current to flow into the power plant's distribution system. Transformers, which consist of two coils of wire with different numbers of loops, are used to raise the current's voltage, because high voltage transmission is more efficient. Other transformers reduce the voltage before the power is delivered to consumers.

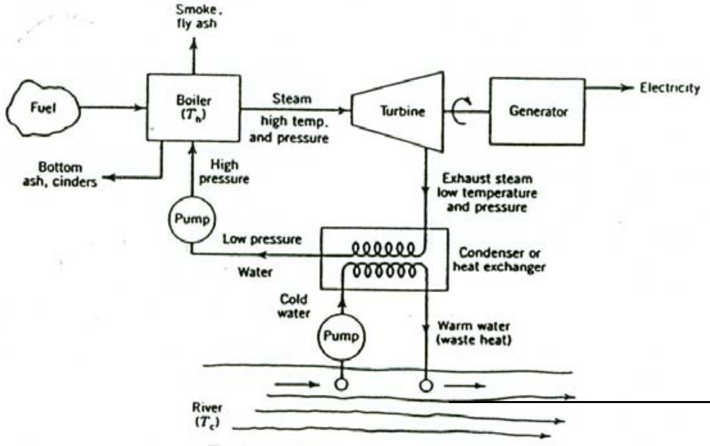

Figure 1. Schematic of a fuel-burning steam-cycle power plant, with once-through cooling using river water.

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[2] Tri-State also operates the Craig Station near Craig, Colorado. It is rated at 1274 MW. The largest steam-cycle power plant in the world is the Kashiwazaki-Kariwa nuclear complex in Japan, which is rated at 8206 MW.

[3] The steam is superheated (heated above its boiling point) because it uses some of its heat energy to spin the turbine blades. Without superheating, the steam would condense in the turbine, and the liquid droplets would destroy the turbine's blades.

[4] One could also attach the magnets to the turbine shaft and mount the coils of wire in the walls.

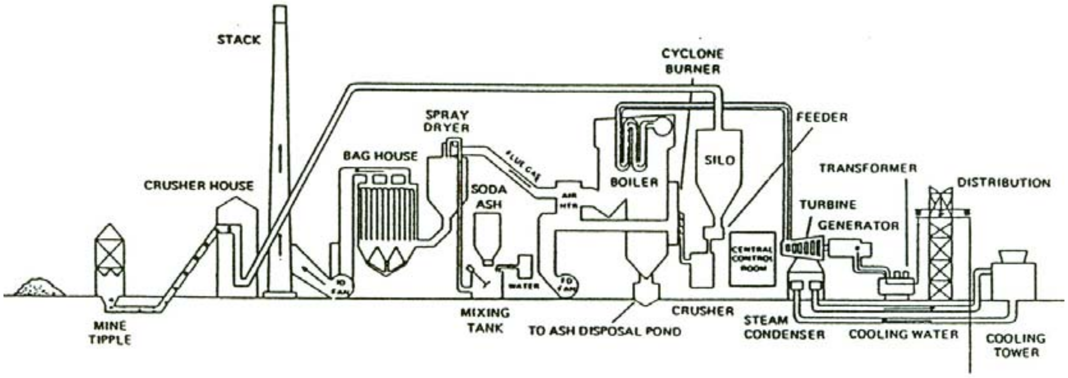

Figure 2. Equipment arrangement in a mine-mouth, coal-fired power plant. Note the soda ash acid-gas scrubber and the cooling tower.

Overall, about one-third of the energy contained in the coal is available for use as electricity. The rest is used (or lost) during the conversion processes. The largest loss (35% to 40%) is heat removed from the steam that is exhausted from the turbine. Steam leaves the turbine at approximately 600 °F and is then condensed into liquid water, by cooling it with water from a pond, stream, or cooling tower. The cooling water becomes hot or even evaporates, transferring waste heat into the environment. Sometimes air is used to condense the steam, which transfers the heat directly to the plant's surroundings.

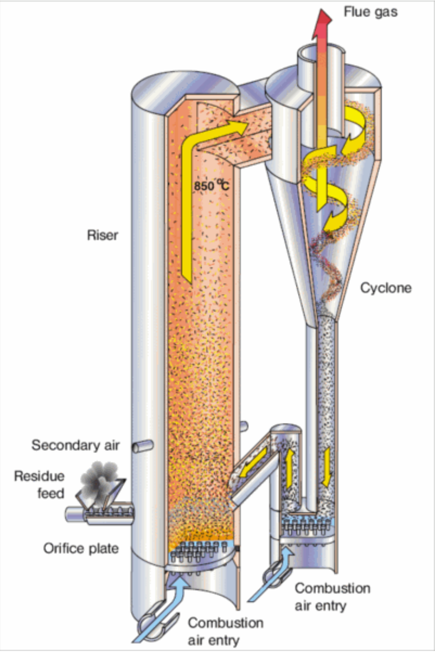

Figure 3. Flow diagram for a Power-Fluid® circulating fluidized bed boiler

Condensation is employed to increase the plant's efficiency[5] and to facilitate handling of the spent steam, which must be pumped back into the boiler. Condensation is important because the work done by a pump depends on the volume of fluid to be pumped. Condensing the steam to liquid water reduces its volume 1000 times. If this were not done, the condensate return pump would have to be much larger and would use much more energy.

About 20% of the energy in the coal is emitted as waste heat from the surfaces of pipes and insulation and leaves as sensible heat in the combustion gases. Other losses occur because of pump inefficiencies, friction, and other sources. Electricity is also lost from the lines that carry power to the ends users, but these transmission losses can be small (less than 1%) if the electricity is transmitted at very high voltages.

Fluidized Bed Power Plants

Most large, modern utility plants in the United States use the pulverized coal (PC) boiler technology described in the previous section. A few other generating stations use circulating fluidized bed combustion technology. A fluidized bed combustion boiler (Fig. 3) is a cylindrical vessel in which relatively coarse particles

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[5] Thermodynamic efficiency depends on the temperature difference between a hot reservoir (the power plant's boiler) and a cold reservoir (the source of the cooling water or air).

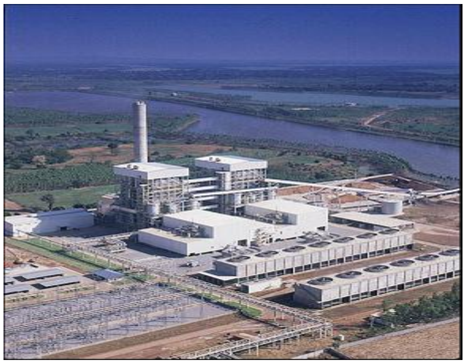

Figure 4. 300 MW National Power Supply plant in Thailand. Two CFBC boilers. Completed Feb. 1999

of a fuel are suspended in a rising stream of hot air, together with another substance, which may be an inert material (such as sand) or a material that absorbs pollutants (such as limestone or soda ash). The bed is constantly in motion, such that it resembles a boiling fluid. The fuel particles burn until they become small enough and light enough to be swept from the vessel in the stream of combustion gases. The gases pass through separators (usually cyclone separators), which remove the particles from the gases. In a circulating fluidized bed combustion boiler (CFBC boiler), the particles removed from the exhaust stream are returned to the boiler. They continue to circulate until they are too small to be separated, at which point they leave the system and are sent to disposal.

The heat of combustion is transferred to water, which forms steam, which spins turbines, which turn generators, which make electricity, just as in a PC system. Figure 4 shows a large CFBC power plant in Thailand. The largest CFB boilers are at the Northside Generating Station in Jacksonville, Florida. The two units produce about 265 net megawatts each.

Fluidized bed boilers have several important advantages over PC boilers. These include:

- The technology is very flexible. Units have been designed to burn anthracite and bituminous coal, peat, lignite, tailings from coal washing, wood waste, heavy oil, tar sands, solid wastes, tire rubber, petroleum coke, oil shale, and other fuels.
- Crushing and grinding costs are relatively low. PC boilers require fuel particles smaller than ¼-inch (6 mm); FBC boilers can burn particles about 3 inches (76 mm) in size.
- Turbulence in the bed improves access of the fuel particles to combustion air, thus accelerating combustion and making conditions in the bed more uniform, which in turn improves heat transfer and steam generation.
- The boiler operates at lower temperatures than a PC boiler. This reduces heat losses and the formation of oxides of nitrogen, a serious air pollutant that is closely regulated in many countries.
- If the fuel contains sulfur, an absorbent mineral such as limestone or soda ash can be circulated with the fuel, to absorb the sulfur dioxide as it is produced. This reduces emissions of acid-forming gases and often can reduce or even eliminate the need for scrubbers, precipitators, and bag houses. This decreases the system’s capital and operating costs.
- CFBC boilers are less susceptible to minerals in the fuel ash that cause slagging and fouling. These minerals melt at the high temperatures used in PC boilers, and they can freeze on the tubes that contain the water. This fouling reduces heat transfer efficiency and increases maintenance costs.
- Some fuels (including oil shale from Colorado’s Green River Formation) contain their own carbonate minerals, such as dolomite, limestone, and nahcolite. When burned in a CFBC boiler, these fuels are “self-scrubbing” meaning they absorb acidic gases produced as they burn, using absorbents that they carry with them.
- If a fuel that contains dolomite or limestone is burned in a PC boiler, the high temperatures can cause thermal decomposition of the carbonate minerals, thereby increasing the amount of carbon dioxide (CO_2) released. This release is bad because CO_2 can contribute to climate change and because the decomposition reaction absorbs energy and reduces the amount of steam (and electricity) that can be produced.

- CFBC boilers have fairly high turndown ratios, meaning that they can operate efficiently above or below their design capacities. This is important because the physical and chemical properties of solid fuels can vary substantially from point to point in a deposit. It may be difficult to regulate the properties of the fuel which, in an intolerant boiler, could cause operating problems.

Fluidized bed reactors have been used for many years in industries such as petroleum refining. Many modern refineries, for example, use a fluid coking process to crack heavy oil into lighter fractions. Hot heavy oil is charged into a vessel that contains a fluidized bed consisting of particles of petroleum coke. The particles become coated with the oil, which then decomposes to yield gases and another layer of coke. Both gases and coke are continuously withdrawn from the vessel.

Fluidized bed combustion for power generation also has a long history. It originated in the United States, with research starting in the 1930s. The technology advanced rapidly in the 1970s, when the goal was to develop a clean, efficient way to burn poor-quality fuels and reduce dependence on unreliable energy imports. This research gave rise to the addition of limestone to the fluidized bed in order to control sulfur dioxide emissions. CFBC boilers were also a response to increasingly stringent air quality regulations. They emerged in the late 1970s, and most of the initial development work was completed by the mid-1980s. Today hundreds of fluidized bed boilers, with a wide range of capacities, are in place. One of the smallest utility plants is Tri-State's Nucla Station, near Nucla, Colorado, on the state's western edge, near the border with Utah (Fig. 5). Nucla Station has 100 MW of generating capacity and is integrated with Tri-State's other generating stations in Colorado, Wyoming, and New Mexico (Fig. 6).

Nucla was the world's first utility-scale power plant to utilize atmospheric circulating fluidized-bed combustion. The station was built between 1957 and 1959 as a test facility for the new CFBC technology. It was re-powered in 1985-87 and has run as a production facility ever since. Total project cost was $112 million. The plant occupies 60 acres of ground and employs more than 50 people. Water is drawn from the San Miguel River and Trout Lake. Low sulfur coal is obtained from the New Horizon Mine, a truck-and-shovel surface mine about 5 miles away. The bed material absorbs about 70% of the sulfur that is released. A fabric filter baghouse collects 90% of the particulate matter.

Figure 5. Tri-State's Nucla Station near Nucla, Colorado. One 100 MW CFBC boiler.

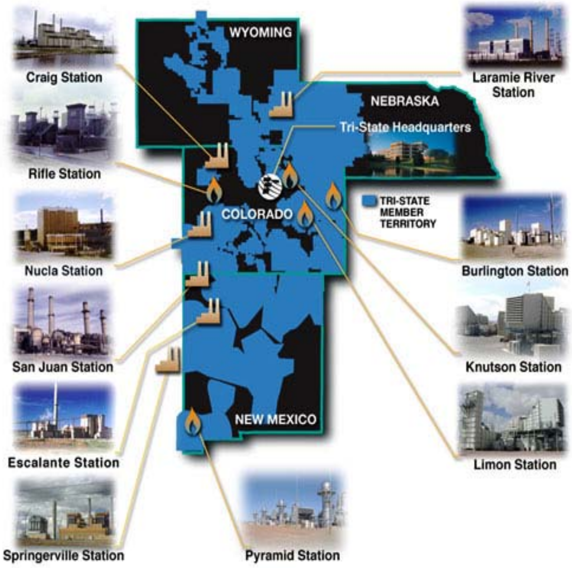

Figure 6. Generating facilities of Tri-State Generating & Transmission Association

Coal Usage in Everyday Activities

The unit trains that supply coal-fired power plants typically have 100 cars, each carrying 100 tons of coal. People are accustomed to the sight of these trains, especially at railroad crossings in Colorado, Wyoming, and other coal-producing states. Seldom do viewers associate the coal with their own electricity consumption.

Table 1 shows the coal requirements associated with common everyday activities. (It is assumed that all of the electricity consumed in those activities is produced from coal.) The costs may be surprisingly low (32 cents to run a personal computer all day; 10 cents to mow the lawn), but the quantities of coal consumed may be surprisingly large. Running that computer requires a power plant to burn 3.5 pounds of coal, enough to fill more than three Starbucks vente cups. Running a refrigerator for one day consumes 10 cups of coal and releases 24.2 pounds of carbon dioxide. Running it for a year burns 2.4 tons of coal and releases 4.4 tons of CO_2 – just to keep your beer cold and the tofu from spoiling.

A Possible Future

In 2006, according to USDOE's Energy Information Administration (EIA), coal provided less than 23% of the nation's primary energy, which is the energy used for all purposes (transportation, industry, residential and commercial, and electric power generation). This is much less than petroleum's overall share of 40%. Coal dominated the electric power area, however, providing fuel for 49% of total electrical generation. Its nearest competitor – natural gas – produced less than 20% of total electricity. Petroleum made less than 2%.

The energy mix may change substantially in the future, as prices shift, supplies rise and fall, and the priorities established for environmental protection, energy security, economic wellbeing, and other social and political factors wax and wane. Despite all this shape shifting, however, some experts expect coal to continue to play a vital role. Figure 7 shows a scenario assembled by the Edison Electric Institute, a public information and lobbying association of shareholder-owned electric companies.

By 2030, contributions of natural gas and nuclear are expected to shrink substantially, and those of hydro and fuel oil will drop slightly. Contributions of non-hydro renewables (solar, wind, geothermal, biomass, and many other sources) could more than double but will still remain relatively small in the overall mix. Coal's role is expected to increase from 49.1% in 2006 to 54.2% in 2030. Given that there will be many more Americans in 2030, this means much more coal will be mined, moved, and burned, and it probably means more hang time at those railroad crossings.

Table 1: Coal Consumed by Everyday Activities

	kWh Used	Coal Burned lb	CO2 Released lb	Cost, ¢
Computer use (8 hr)	3.2	3.5	6.46	32
Room air conditioner (8 hr)	8.0	8.8	16.1	80
Shower (electric water heater)	7.9	8.7	16.0	79
Brew pot of coffee	0.7	0.8	1.0	7
Microwave a meal (30 min)	0.5	0.6	1.0	5
Fluorescent office lights (8 hr)	1.6	1.8	3.2	16
Refrigerator (24 hr)	12.0	13.2	24.2	120
Electric hand dryer (3 min)	0.11	0.13	0.23	1
Electric lawn mower	1.0	1.1	2.0	10
Launder one load of clothes	8.0	8.8	16.1	80
Wash dishes twice	2.25	2.5	4.5	23
Charge electric car	250	276	504	2500
Cook dinner on range (3 hr)	37.5	41.3	75.7	375
Vacuum (1 hr)	0.5	0.6	1.0	5
Iron clothes (2 hr)	2.0	2.2	4.0	20

Note: Starbucks' vente cup (24 oz, cold) would hold about 1.3 pounds of broken coal

Assumes:

Coal heating value of 10,555 Btu/lb. Heat rate 6.67 kWh/kg of coal burned.

Power price $0.10 per kWh. Conversion efficiency 30% (national average)

Estimated by Rachel des Cognets, Colorado School of Mines, 2007.

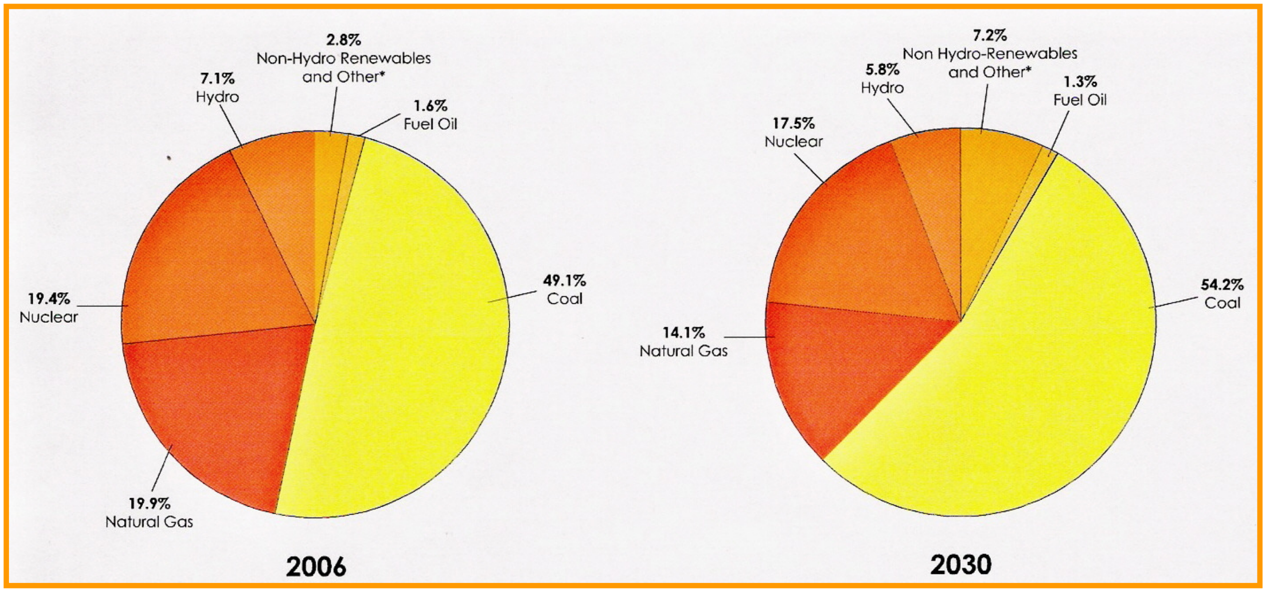

Figure 7. Energy for electric power generation

From *Powering America's Electric Future*, Edison Electric Institute, 2008. Sources included EIA's *Annual Energy Outlook 2008*, *Combined Heat and Power Report*, *Electric Power Monthly*, and *Electric Power Annual 2007*.