Chapter 2

Coal Creates Power and Light

Lights! Action!

In this unit, we explore the use of fossil fuel technologies during the 19th century that revolutionized the lives of millions of people by making manufactured goods and lighting affordable.

Why Do I Need to Know This?

In this chapter, you learn how the concentrated energy in coal was applied to the tasks of manufacturing, transportation, and lighting. This combination of fossil fuel energy and technology separated the developed countries from the rest of the world in power, wealth, and comfort. The information in this chapter will help you understand the challenge faced by undeveloped countries that do not have deposits of coal to develop without it.

1 Physics of Steam and Evaporation

Learning Objectives

1. Identify the different states of water, including water vapor. [2.1.1]
2. Identify the relationship between water, steam, and pressure. [2.1.2]
3. Describe the process of evaporation and how it differs from boiling. [2.1.3]
4. Describe relative humidity and how evaporation is affected by humidity. [2.1.4]
5. Describe how evaporation is used for cooling. [2.1.5]

Coal was useful for home heating but its real advantage over wood was the ability to produce high temperature fires that could be used to melt metals or produce large quantities of high-temperature steam. Steam was used to force pistons back and forth in cylinders. This back and forth motion was converted into rotary motion by attaching the piston to the side of a wheel and the rotary motion was used to power any kind of machine that uses wheels as shown in Figure 2.1.

Figure 2.1. Early steam engine.

To understand steam engines, you must have a basic understanding of water. In this section, we review the basic science concepts used in technologies that are related to steam. We are familiar with water as a liquid and a solid (ice). The other two forms of water are not as well understood. Water can exist as a gas in two distinctly different ways. Water molecules can be mixed with the nitrogen and oxygen molecules in the atmosphere in which case we call it water vapor. If a quantity of water is heated enough to separate its molecules into a gas, it is called steam.

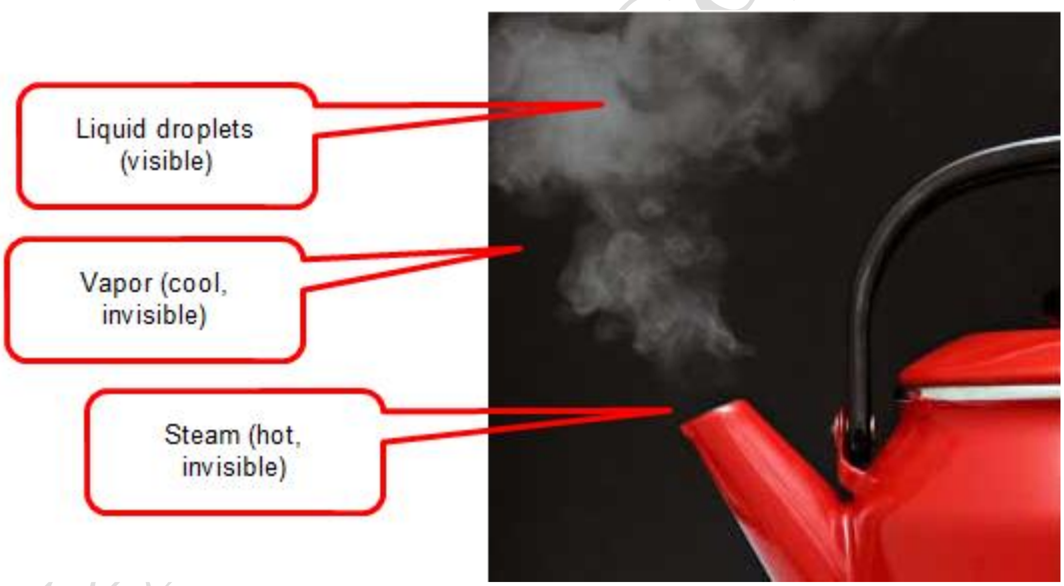

Figure 2.2. Steam, vapor, and liquid.

Steam is not visible. If you could see inside a tea kettle that contains rapidly boiling water, the space above the water would be clear. Similarly, inside a steam engine, the steam is clear. When the steam cools, it can condense into drops of liquid water that are visible. Those droplets usually dissolve into the surrounding air to become water vapor and they disappear. Clouds are suspended water droplets.

If you heat a volume of water and increase the rapid motion of its molecules enough, the molecules fly apart and form steam. Steam occupies one thousand times as much volume as an equal mass of liquid water at the same pressure. Alternatively, if you confine the steam to a smaller volume, its pressure will increase greatly.

Recall that heat is the rapid motion and vibration of atoms and molecules. The amount of motion is not equally shared between the molecules—some of them move much faster and others move much slower. Because water molecules attract each other, they tend to stay together in a liquid or solid unless they are heated sufficiently.

Liquid water can change into water vapor at room temperatures. At the boundary between liquid water and the atmosphere, some of the faster molecules of water move fast enough to break free of their attraction to other water molecules and fly off into the air, as shown in Figure 2.3.

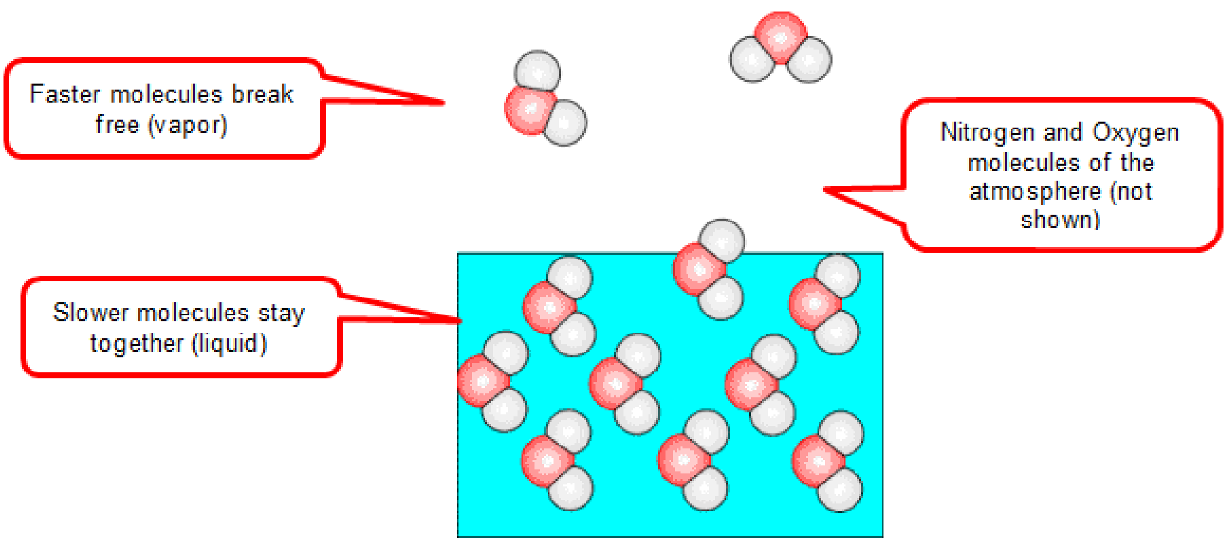

Figure 2.3. Evaporation.

This process is called evaporation. You can think of this as the water being dissolved into the air like sugar is dissolved in hot water.

- Relative Humidity: The amount of water that is dissolved is called humidity. Hot air can hold more dissolved water than cold air. A ratio of how much water a given volume of air does hold to how much it could hold is its relative humidity which ranges from zero to 100%.
- Condensation: If the air is cooled and there is more water in it than it can hold at its lower temperature, the water condenses and forms droplets of liquid water. When warm, humid air rises and

gets colder, water droplets form that we perceive as clouds.

- Evaporative cooling: When the fastest molecules escape from the liquid, the average motion of the remaining molecules is less. Recall that this average is the temperature. Thus, evaporation cools the remaining liquid. Our bodies use this method to cool by evaporating sweat from our skin.

Key Takeaways

- Water can be a solid (ice) and a liquid. When heated sufficiently, it can boil into steam. Water molecules can be dissolved in other gasses like those that make up the atmosphere and then it is referred to as water vapor. [2.1.1]
- Steam will take up one thousand times the volume of water if allowed to expand. If contained and not allowed to expand very much, high pressures result. [2.1.2]
- If heat is added to liquid water to raise its temperature to the boiling point, it will turn into a gas called steam. This can happen when no other liquids or gasses are present. If water is exposed to the atmosphere, a few of its most energetic molecules can break loose of the rest and mix with the atmospheric gasses. This is called evaporation. [2.1.3]
- The ratio of the amount of water vapor that is dissolved in the atmospheric gasses to the maximum amount that the gasses could hold at a given temperature is the relative humidity. The capacity of air to hold water depends on its temperature—warmer air can hold more water. [2.1.4]
- If the fastest water molecules are allowed to evaporate, this lowers the average energy of the remaining water molecules. The average energy is the temperature so evaporation cools the remaining liquid. [2.1.45]

2 Coal Makes Steam for Industry

Learning Objectives

1. Identify the difference between firetube and watertube boilers and their uses. [2.2.1]
2. Identify the devices used to convert the expansion of steam into rotary motion. [2.2.2]
3. Identify the areas of the world that have abundant coal deposits. [2.2.3]
4. Describe how smoke stacks are used to manage exhaust gasses. [2.2.4]

To make steam, heat is added to water. The water is enclosed in a boiler and the heat is transferred into the water via a heat exchanger. There are two main types of boilers whose names reflect the type of heat exchanger used:

Firetube Boiler: The hot exhaust gasses from a fire pass through metal tubes that are surrounded by water. The heat from the hot gasses passes through the metal tubes into the water and the water boils into steam. The firetubes are shown in Figure 2.4. The hot gasses from the fire pass through the tubes. Water surrounds the tubes and is turned into steam by the heat. This design is used in steam locomotives and boilers used to provide steam for local heating.

Figure 2.4. Firetube boiler.

Watertube boiler: In a water tube boiler, the situation is reversed. The water is inside the tubes and the hot gasses flow around them. Watertube boilers are used for large installations like a coal power plant.

The high pressure steam from the boiler can be released into a cylinder where it pushes a piston along the cylinder. A series of pipes and valves can route the steam to the other side of the piston and push it in the opposite direction while a valve releases the low pressure steam to the atmosphere. The piston is connected to the side of a wheel by a connecting rod. The back and forth motion of the piston is transformed into the rotary motion of the wheel as shown in Figure 2.5. (Steam Engine 2008) [Link]

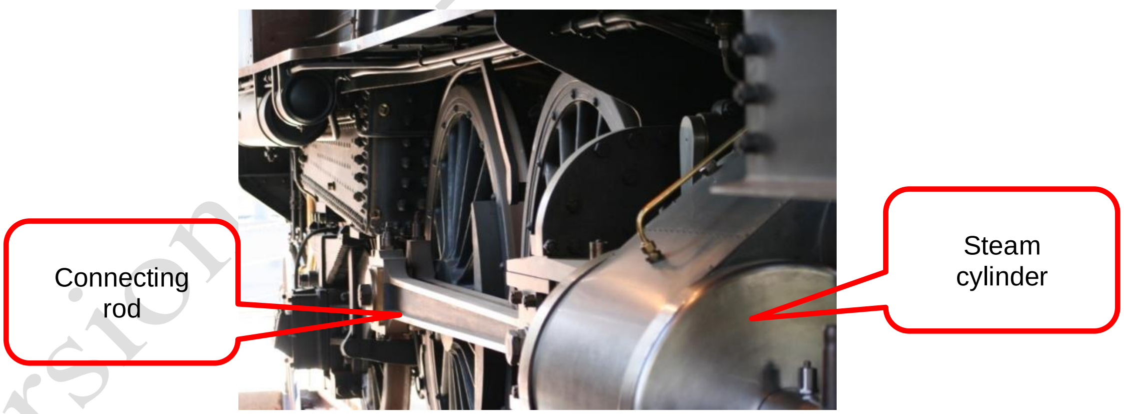

Figure 2.5. Steam locomotive.

The rotation of the wheel can be transferred to manufacturing machines using belts and pulleys, as shown in Figure 2.6.

Figure 2.6. Energy from the steam engine transmitted to machines by belts and pulleys.

Improved design of steam engines made them smaller and more efficient. In the early 1800s steam engines powered by coal were used in ships primarily on rivers where sail boats could not maneuver or move up river against the current. Ocean-going steam ships became common in the mid-1800s. Because steam powered ships could travel against wind and tide and take direct routes, they could travel around the world in about two months compared to two years for a sailing ship.

In the early 1800s steam locomotives were invented to pull trains of cars on a set of rails. Because the steam engine used water and coal, the use of steam power for transportation was limited to vehicles that could carry tons of weight such as ships or trains.

Coal Resources

In the 1800s, coal was the primary energy resource of the industrial age. If a country had coal, it could build industries based on refining metal, manufacturing, and transportation. Britain, Germany, France, and the United States developed rapidly in the 1800s. Russia, China, Canada, and Australia also have large deposits of coal, as shown in Figure 2.7. (World Coal Deposits 2007) Observe from the map that South America, the Middle East, western Africa, and Japan have minimal amounts of coal.

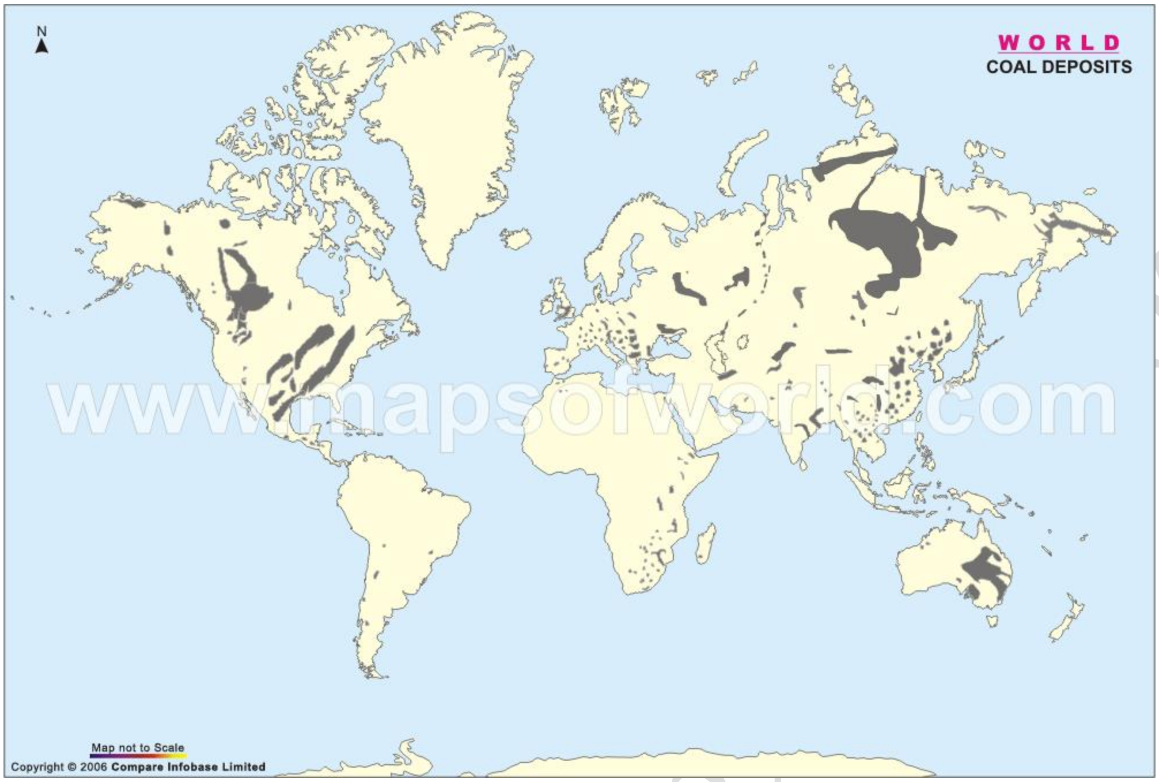

Figure 2.7. Coal deposits.

Air Pollution from Industrial use of Coal

Legislation in many countries limits the amount of fly ash and noxious gasses that are in the air near the plant—not the amount that the plant actually emits. A common method of reducing the concentration of pollution near the plant is to build very tall smoke stacks, like the one in Beijing China shown in Figure 2.8.

Figure 2.8. Tall smoke stacks dilute gasses over a large area.

By the time the smoke reaches the ground, it is dispersed over a wide area and the concentration of the ash and gasses from that plant is below the legal limit. This philosophy is represented in the phrase "The solution to pollution is dilution." This approach has a local focus and does not demonstrate global awareness. Tall stacks introduce the smoke into air currents that travel around the world. Stack height is limited in ships and trains and they rely on spreading the smoke by constantly changing location.

Key Takeaways

- In a firetube boiler, the hot exhaust gasses from the fire pass through the tubes which are surrounded by water that boils and turns into steam. Firetube design is used in locomotives and smaller boilers for heating buildings. In a watertube boiler, the exhaust gasses from the fire circulate over tubes that contain water. The watertube design is used for large coal fired power plant boilers. [2.2.1]
- High pressure steam is fed into a cylinder where it pushes a piston. The piston is connected via a connecting rod to a flywheel. The steam can be diverted to either side of the piston making it go back and forth in the cylinder. The connecting rod converts this motion into rotation of the flywheel. [2.2.2]
- Large amounts of coal are found in north America, Europe, Russia, and Australia. [2.2.3]
- Smoke stacks are used to spread the exhaust gasses and the pollutants in them over a large area to reduce the concentration locally to meet local requirements. [2.2.4]

3 Coal Makes Steam for Electricity and Lighting

Learning Objectives

1. Identify the roles of conductors, insulators, and resistors in electrical systems. [2.3.1]
2. Identify the difference between AC and DC electricity. [2.3.2]
3. Identify the similarities and differences of generators and motors. [2.3.3]
4. Identify the relationship between electricity, magnetism, and light. [2.3.4]
5. Describe the process by which coal is used for electrical lighting. [2.3.5]

The age of the kerosene lamp ended when the technology of steam power was combined with the technologies of generating electricity and the electric light bulb. The advent of electric lighting produced another dramatic shift in the way people lived and restored coal as the primary source of fuel for lighting.

Physics of Electricity and Magnetism

To understand how electricity is generated and how it is used for lighting, you need to know more physics. The electrons that form the outer layers of atoms stay fairly close to the nuclei of most atoms and molecules. An exception is when the atoms form a three dimensional crystal and the outermost electrons are free to roam about the crystal without a strong attraction to any individual nucleus. Metals such as copper, aluminum, silver, and gold are actually crystals that have this property.

When a material allows electrons to move easily, it is called a conductor. Magnets can exert a force on electrons in a conductor and cause them to move in one direction or to shove their neighboring electrons in that direction through mutual repulsion. When they do, we call this organized motion, electricity.

Magnets have a north and south pole which have opposite effects on the motion of the electrons. If we make wires out of copper and spin a magnet inside the coils of wires, the electrons flow first one way and then the other as the north and south poles pass by. We call this alternating motion of the electrons, alternating current (AC). North America, the electricity is generated so that the direction of the electricity alternates 60 times a second while in Europe it alternates 50 times per second. A simple switching device can route the electrons so they travel in one direction which we call direct current (DC).

The device that contains the magnet and coils of wires that converts spinning motion into electric current is called a generator.

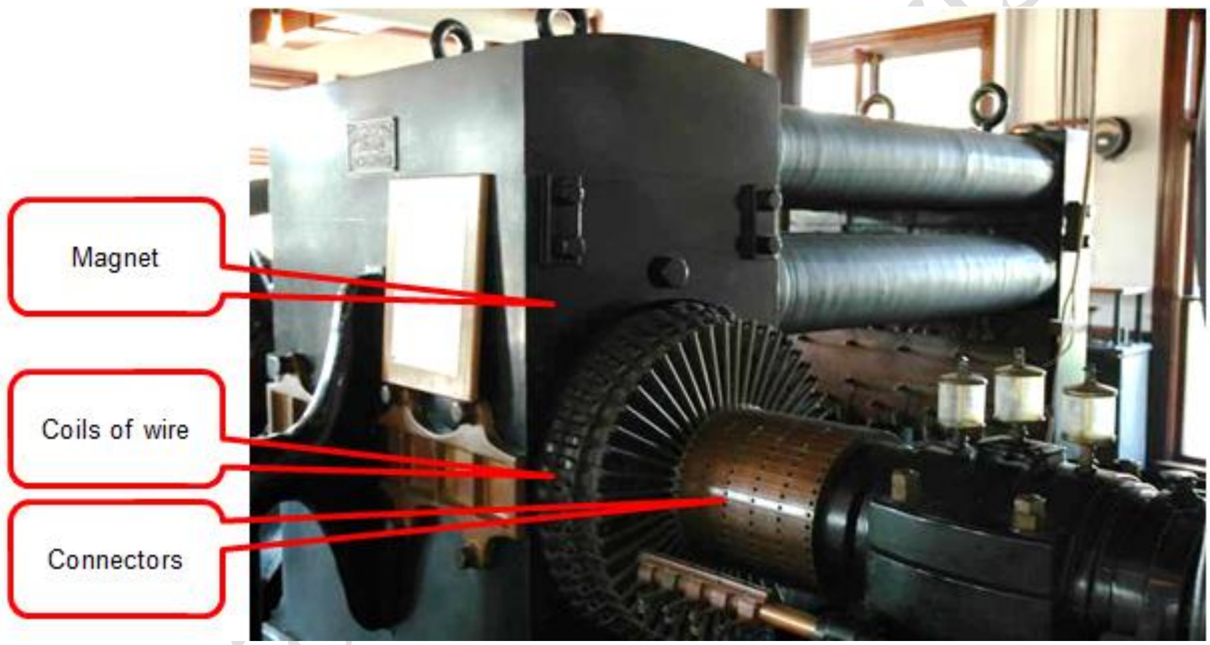

Figure 2.9. Early DC generator.

The nuclei of most atoms and molecules hold onto their electrons and they do not conduct electricity. These materials are called insulators. Conductors are often enclosed in insulators, as shown in Figure 1.10.

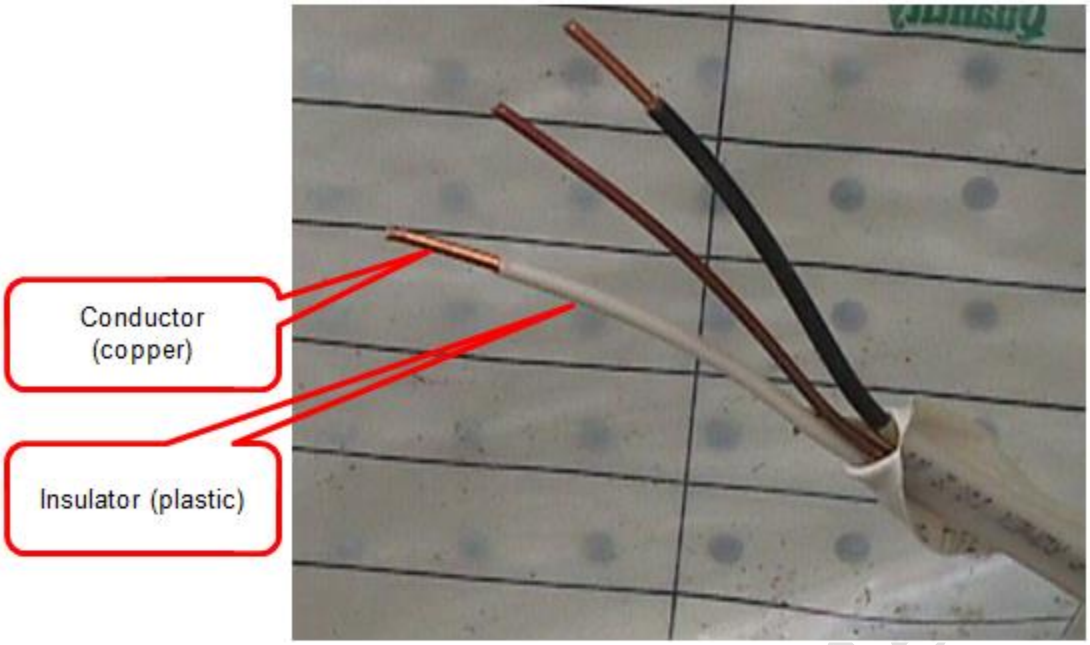

Figure 2.10. Conducting copper wire enclosed within insulating plastic.

Glass and plastic are examples of insulators. Some materials are in between. They allow the electricity to flow through them but they resist more than conductors. We call them resistors. If we force electricity through resistors, the energy of the electricity turns into heat. The heating element in a toaster has resistance that converts electrical energy into heat, as shown in Figure 2.11.

Figure 2.11. Resistor in a toaster glows red-hot.

Electricity and magnetism have a remarkable relationship to each other. When electricity flows through a wire, the wire is surrounded by magnetism. This type of magnetism can be turned on and off by switching the electricity on and off.

If a coil of wire is placed around a magnet, the magnet can be made to spin by turning the current on and off. Instead of turning the current on and off, we can use alternating current in the coils of wire to make the magnetism of the coils reverse causing the magnet to keep rotating seeking to line up with an ever-changing magnetic field. If the spinning magnet is attached to a shaft, we can use this spinning shaft to power machines or other devices. This combination of a coil and spinning magnet is an electric motor. Notice the similarity in construction between a generator and a motor in Figure 2.12. Both have coils of wires and a rotating magnet.

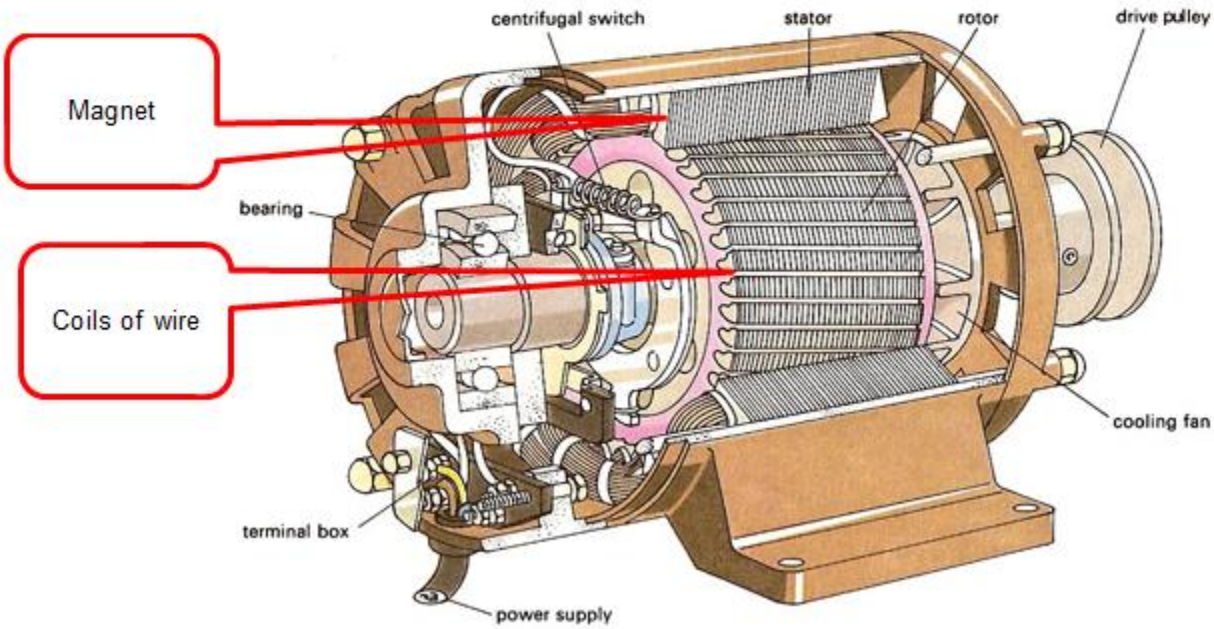

Figure 2.12. Electric motor

The remarkable relationship between electricity and magnetism is even more strange and unusual. Early scientists could show that electric current made a magnetic field and that a moving magnetic field could produce an electric current. In a brilliant insight, James Maxwell conceived the idea that light itself was made of electric and magnetic fields that could generate each other as each one grew and collapsed in waves of energy. We now know that visible light is simply a particular range of wavelengths of electromagnetic energy and to produce light, all you have to do is to accelerate a charged particle such as an electron. This explains why hot objects emit visible light—the charged particles in the atom are constantly changing speed and direction as the bump into each other. The faster they are going when they collide, the more energy they impart to the photons of light they emit and the shorter their wavelengths.

Electricity for Lighting, Cooking, and Work

If you take a material that is a resistor and run electricity through it, the energy of the organized electricity will turn into the unorganized motion of the atoms and molecules in the form of heat. If the material gets hot enough, some of the collisions of the charged particles create electromagnetic waves that are short enough to be visible. When a material is hot enough to give off visible light, it is incandescent. The problem is that most materials will either vaporize or oxidize (burn up) at those temperatures. One of Thomas Edison's discoveries was that a cotton thread could be carbonized in the same manner that one makes charcoal out of wood. The resulting carbonized fiber will glow white hot giving off light. If the fiber is enclosed in a glass bulb from which the oxygen has been removed, it won't oxidize quickly. Thus, Edison invented the first practical light bulb. This was only part of the invention. Edison combined and improved upon several other inventions to create a lighting system. The system had a coal-fired steam boiler that turned the generator, a distribution system of copper wires, and lamps that held electric light bulbs. A powerhouse, like the one shown in Figure 2.13, had a boiler, a steam engine, and an electric generator.

Figure 2.13. Early Edison power house

Conducting wires carried the electricity through the town while protected by insulation. The electricity was connected to the new light bulbs. The new electric lights were easily controlled with switches, were brighter, and much safer. Within a few decades, kerosene lamps were replaced by electric lights.

Resistance elements in an electric stove convert electricity into heat. The temperature isn't as high and the elements are much thicker than the filament in a light bulb so they don't vaporize but they do get hot enough to give off some visible light. Most of the heat is transferred by direct contact with a pan or is trapped in an enclosed oven. Cooking with electricity removes the smoke and exhaust gasses from the home entirely and concentrates them in power plants where they can be cleaned more effectively, as shown in Figure 2.14.

Figure 2.14. DTE Energy power plant at Monroe Michigan

Electric motors can be large or small. They are used in industry to power machinery and in our homes to run the fan on the furnace and the compressor in the refrigerator.

About 38% of the electricity power plants in the world burn coal to make steam. In the U.S., 50% of the electricity is generated using coal. (The Cost of Coal 2002) Electricity is distributed to cities and homes via a network of wires. Consider the composite image shown in Figure 2.15. It is made of night-time images of the earth from space that shows the pattern of electric lighting around the world. (Earth at Night 2006) [Link]

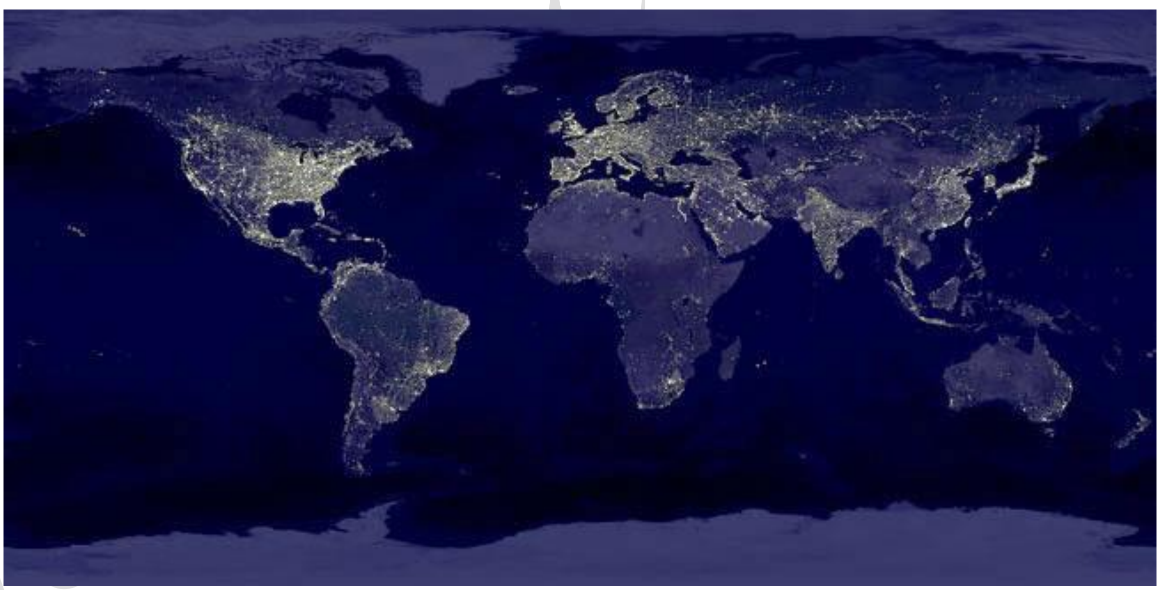

Figure 2.15. Composite of night time photos of earth shows use of electric lighting

Key Takeaways

- Conductors transfer electric energy. Insulators prevent unwanted transfer of electricity. Resistors transfer electricity but not as easily as conductors. The resistors get hot so they can be used as heating or lighting elements. [2.3.1]
- Alternating current (AC) changes directions while direct current (DC) maintains flow on o ne direction. [2.3.2]
- Generators convert rotational energy into electrical energy. Motors convert electrical energy into rotational energy. Both use magnets, coils of wire, and a shaft. [2.3.3]
- Changing electric and magnetic fields can create each other. James Maxwell perceived that photons of light were small bundles of electric and magnetic fields and that accelerating a charged particle like a electron or ion could create these photons. If they had enough energy, they would be visible. [2.3.4]
- Coal can be burned at high temperature to make steam. The steam can be used to turn a generator that creates electricity. The electricity is transferred to buildings where it can be used to heat the filaments in electric light bulbs to produce light. [2.3.5]

Key Terms

Alternating current

electricity that changes direction periodically

Boiler

container in which water is changed from liquid to steam

Condensation

water vapor coming out of solution in the air to form drops of liquid water

Conductor

allows electrons to move freely within its structure

Direct current (DC)

electricity that maintains one direction

Electricity

the organized movement of electrons

Electromagnetic energy

a form of energy of motion that consists of electric and magnetic fields that self-generate and propagate

Evaporation

transfer of faster water molecules into the atmosphere

Generator

device to convert rotary motion of a shaft into electricity

Incandescent

hot enough to emit visible light

Insulator

allows very little electricity to flow through it

Relative humidity

the ratio of the amount of water vapor dissolved in air to the maximum amount that could be dissolved at that temperature and pressure

Resistor

allows electricity to flow but not as easily as a conductor

Steam

water in its gaseous state

Water vapor

water molecules mixed with air

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Last edited on September 16, 2011