CHAPTER 11

The Electric Age

11.1 TRANSPORTING ENERGY FROM ONE PLACE TO ANOTHER

In Chapter 6, we discussed the development of steam engines during the eighteenth and nineteenth centuries. These engines enabled industrialization by making available the vast stores of energy contained in coal, wood, and oil. By burning fuel, chemical energy is converted into heat energy, which in turn can be used to boil water to produce steam. By letting the steam expand against a piston or a turbine blade, heat energy can be converted to mechanical energy. In this way, a steam engine can power machinery.

Steam engines had two major defects, however. First, the mechanical energy was available only at the place where the steam engine was located. Second, practical steam engines were big, hot, and dirty. As the use of machines run by steam engines increased, people were crowded together in factories, and their homes stood in the shadow of the smoke stacks. Even steam-powered locomotives, though useful for transportation, were limited by their size and weight. They also added further air pollution.

Using one central power plant for sending out energy for use at a distance could partially overcome these defects. The energy transmitted by the central power plant could drive machines of any desired size and power at the most practical locations. After Volta's development of the battery, many scientists and inventors speculated that electricity might provide such a means of distributing energy and running machines. But the energy in batteries is quickly used up unless it is delivered at a low rate. A better way of generating electric currents was needed. When such a way was found, it changed the whole shape of life in homes, factories, farms, and offices. It even changed the very appearance of cities and landscapes.

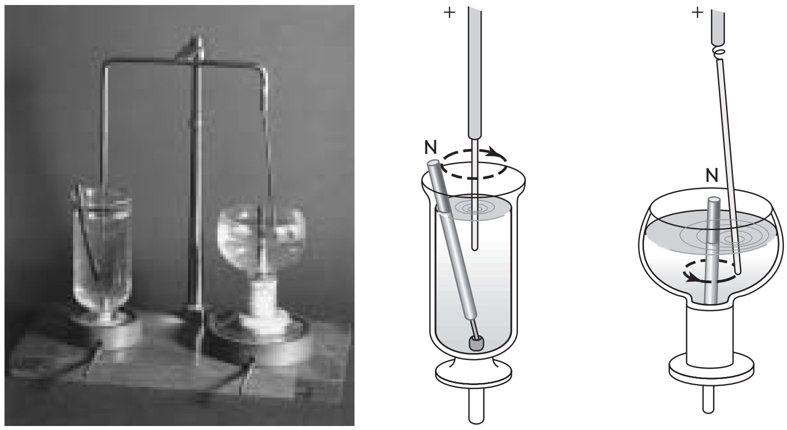
In this chapter you will see another example of how discoveries in basic physics have given rise to new technologies. These technologies have revolutionized and benefited modern civilization. But they have brought some new problems in their turn.

The first clue to the broader use of electricity came from Oersted's discovery that a magnetic needle is deflected by a current supplied by a battery to a conductor. It was quickly realized that since an electric current can exert a force on a magnet, the force might be harnessed to perform useful work. In addition, many physicists naturally speculated that a magnet could somehow produce a current in a wire. (Such reasoning from symmetry is common in physics and is often useful.) Soon after the news of Oersted's discovery reached Paris, the French physicists Biot, Savart, and Ampère began research on the interactions of electricity and magnetism. (Some of their results were mentioned in Chapter 10.) A flood of other experiments and speculations on electromagnetism poured from all over the world into the scientific journals. Yet the one key discovery—how to generate an ample and continuous electric current—still eluded everyone.

11.2 FARADAY'S FIRST ELECTRIC MOTOR

Scientific journals regularly print brief announcements of the technical details of new discoveries. From time to time they also provide valuable in-depth surveys of recent broad advances in science. The need for such a review article is especially great after a burst of activity of the kind that followed Oersted's discovery of electromagnetism in 1820.

In 1821, the editor of the British journal *Annals of Philosophy* asked the English physicist Michael Faraday to review the experiments and theories of electromagnetism that had appeared in the previous year. In preparing for this review, Faraday made a remarkable discovery. Repeating Oersted's experiment (Section 10.9), he put a compass needle at various places around a current-carrying wire. Faraday was particularly struck by one fact: The force exerted by the current on each pole of the magnet tended to carry the pole along a circular line around the wire. As he expressed it later, the wire is surrounded by *circular lines of force:* a circular magnetic field.



(a) (b)

FIGURE 11.1 Two versions of Faraday's electromagnetic rotator. In each, the cup was filled with mercury so that a current could be passed between the base and overhead support. In one version (a), the north end of a bar magnet revolves along the circular magnetic lines of force surrounding the fixed current. In the other version (b), the rod carrying the current revolves around the fixed bar magnet, moving always perpendicular to the magnetic lines of force coming from the pole of the magnet.

Faraday then constructed an "electromagnetic rotator" based on this idea. It worked. Though very primitive, it was the first device for producing continuous motion by the action of a current: the first electric motor.

As in many other cases, Faraday was also guided by the idea that for every effect of electricity on magnetism, there must exist a corresponding effect of magnetism on electricity. Of course, it was not always so obvious what form the corresponding effect would take. But it led him to design an arrangement in which the magnet was fixed and the current-carrying wire rotated around it. (If a current exerts a force on a magnet, the magnet should exert an equal force on the current, according to Newton's third law.) This device, too, was eventually developed into a type of electric motor.

11.3 THE DISCOVERY OF ELECTROMAGNETIC INDUCTION

Armed with his idea involving "lines of force" of electric and magnetic fields, Faraday joined the search for a way of producing currents by magnetism. Scattered through his diary in the years after 1824 are many descriptions of

MICHAEL FARADAY

Michael Faraday (1791–1867) was the son of an English blacksmith. In his own words:

> My education was of the most ordinary description, consisting of little more than the rudiments of reading, writing and arithmetic at a common day-school. My hours out of school were passed at home and in the streets.

At the age of 12 he went to work as an errand boy at a bookseller's store. Later he became a bookbinder's assistant. When Faraday was about 19 he was given a ticket to attend a series of lectures given by Humphry Davy at the Royal Institution in London. The Royal Institution was an important center of research and education in science, and Davy was Superintendent of the Institution. Faraday became strongly interested in science and undertook the study of chemistry by himself. In 1813, he applied to Davy for a job at the Royal Institution and Davy hired him as a research assistant. Faraday soon showed his genius as an experimenter. He made important contributions to chemistry, magnetism, electricity, and light, and eventually succeeded Davy as Superintendent of the Royal Institution.

Because of his many discoveries, Faraday is generally regarded as one of the greatest experimental scientists. Faraday was also a fine lecturer and had an extraordinary gift for explaining the results of scientific research to nonscientists. His lectures to audiences of young people are still delightful to read. Two of them, "On the Various Forces of Nature" and "The Chemical History of a Candle," have been republished in paperback editions.

Faraday was a modest, gentle, and deeply religious man. Although he received many international scientific honors, he had no wish to be knighted, preferring to remain without title.

FIGURE 11.2

such experiments. Each report ended with a note: "exhibited no action" or "no effect."

Finally, in 1831, came the breakthrough. Like many discoveries that follow much research and discussion among scientists, this one was made almost at the same time by two scientists working independently in different countries. Faraday was not quite the first to produce electricity from magnetism. *Electromagnetic induction*—the production of a current by magnetism—was actually discovered first by the American scientist Joseph Henry. At the time Henry was teaching mathematics and philosophy at an academy in Albany, New York. Unfortunately for the reputation of American science, teachers at the Albany Academy were expected to spend all their time on teaching and related duties. There was little time left for research. Henry had hardly any opportunity to follow up his discovery, which he made during a one-month vacation. He was not able to publish his work until a year later. In the meantime, Faraday had made a similar discovery and published his results.

But Faraday is known as the discoverer of electromagnetic induction not simply because he was the first to publish his results. More importantly, he conducted exhaustive investigations into all aspects of the subject. His earlier experiments and his ideas about lines of force had suggested that a current in one wire should somehow induce a current in a nearby wire. Oersted and Ampère had shown that a *steady* electric current produced a *steady* magnetic field around the circuit carrying the current. Perhaps a steady electric current could somehow be generated if a wire were placed near or around a very strong magnet. Or a steady current might be produced in one wire by a large steady current in another wire nearby. Faraday tried all these possibilities, with no success.

The solution Faraday found in 1831 came partly by accident. He was experimenting with two wire coils that had been wound around an iron ring (see Figure 11.3). He noted that a current appeared in one coil—called the *secondary*—while the current in the other coil—called the *primary*—was being switched on or off. When a current was turned on in the primary coil A, a current was induced in secondary coil B, but it lasted only a moment. As soon as there was a steady current in coil A, the current in coil B disappeared. When the current in coil A was turned off, a current again appeared briefly in coil B.

To summarize Faraday's result:

> A current in a stationary wire can induce a current in another stationary wire only while the current is changing. A steady current in one wire cannot induce a current in another wire.

Faraday was not satisfied with merely observing and reporting his accidental arrangement and its important result. Guided by his concept of "lines of force," he tried to find out the basic principles involved in electromagnetic induction.

According to Faraday's theory, the changing current in coil A would change the lines of magnetic force in the whole iron ring. The change in

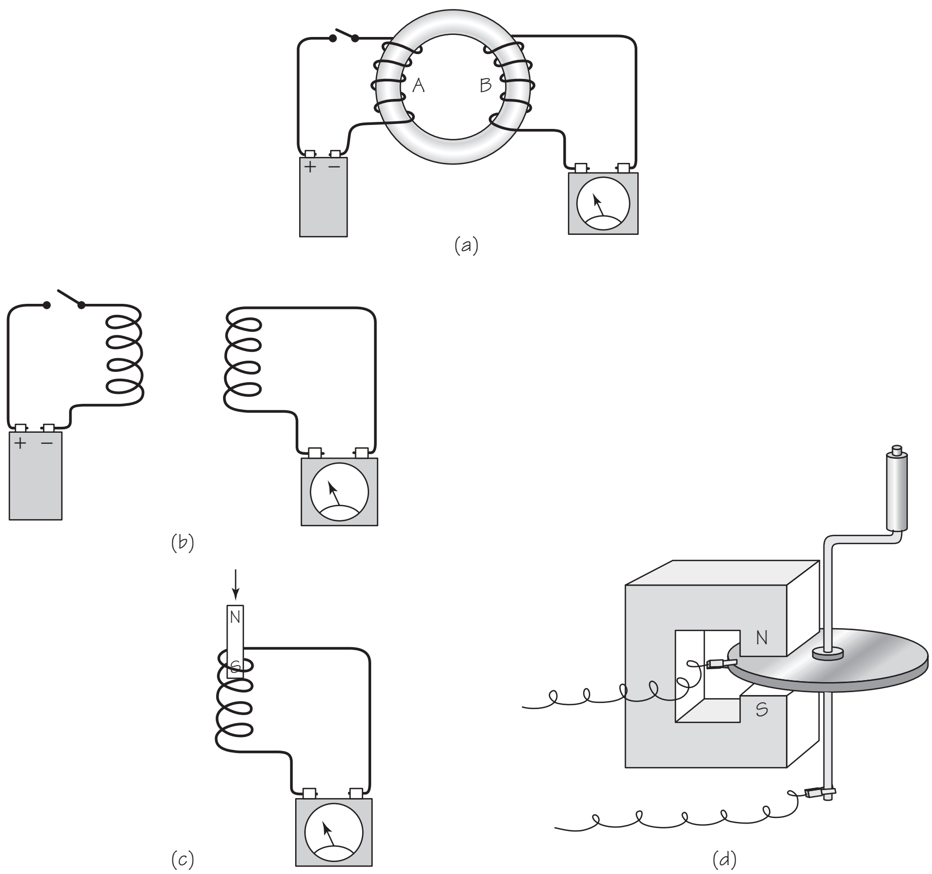


FIGURE 11.3 Various ways of producing electromagnetic induction.

lines of magnetic force in the part of the ring near coil B would then induce a current in B. But if this was really the correct explanation, Faraday asked himself, should it not be possible to produce the same effect in another way? In particular, he asked:

1. Is the iron ring really necessary to produce the induction effect? Or does the presence of iron merely strengthen an effect that would also occur without it?
2. Is coil A really necessary? Or could current be induced simply by changing the magnetic lines of force through coil B in some other way, such as by moving a simple magnet relative to the wire?

Faraday answered these questions almost immediately by performing further experiments. First, he showed that the iron ring was not necessary.

Starting or stopping a current in one coil of wire would induce a momentary current in a nearby coil, with only air (or a vacuum) between the coils. (See the drawing in Figure 11.3b. Note that there is no battery in the circuit at the right in (b), only a meter to measure the induced current.) Second, he studied what happened when a bar magnet was inserted into or removed from a coil of wire. He found that a current was induced at the instant of insertion or removal. (See drawing (c).) In Faraday's words:

> A cylindrical bar magnet . . . had one end just inserted into the end of the helix cylinder; then it was quickly thrust in the whole length and the galvanometer [current-meter] needle moved; when pulled out again the needle moved, but in the opposite direction. The effect was repeated every time the magnet was put in or out. . . .

Note that his arrangement amounted to a primitive *electric generator*; it provided electric current by having some mechanical agent move a magnet.

Having done these and many other experiments, Faraday started his general *principle of electromagnetic induction*. Basically, it is that *changing lines of magnetic force can induce a current in a wire*. The needed "change" in lines of force can be produced either by a magnet moving relative to a wire or by a changing current in another circuit. In the case of the moving magnet, Faraday described the wire in which current was induced as being "cut across" by lines of force from the magnet. In the case of the effect caused by a changing current in another circuit, the lines of force from the latter "cut across" the wire. He later used the word *field* to refer to the arrangement and intensity of lines of force in space. Using this term, one can say a current can be induced in a circuit by changes set up in a magnetic field

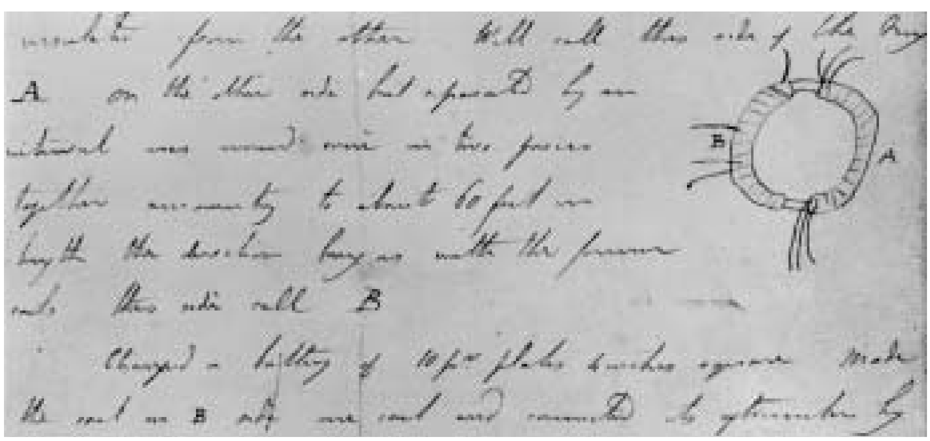


FIGURE 11.4 Detail of a page in Faraday's diary where he recorded the first successful experiment in electromagnetic induction.

around the circuit. Such changes may result either from relative motion of wire and field or simply from a change in intensity of the inducing field.

So far, Faraday had produced only momentary surges of current by induction. This was hardly an improvement over batteries as a source of current. Was it possible to produce a continual current by electromagnetic induction? To do this would require a situation in which magnetic lines of force were *continually changing* relative to the conductor. Using a simple magnet, the relative change could be produced either by keeping the magnet or the conductor in motion. This is just what Faraday did. He placed a copper disk between the poles of a magnet, and applied mechanical energy to keep it turning. (See Figure 11.3d.) A steady current was produced in a circuit connected to the disk through brass contacts or "brushes." His device—called the "Faraday disk dynamo"—was the first constant-current electric generator. While this particular arrangement did not turn out to be very practical, it showed at last that continuous generation of electricity was possible.

These first experimental means of producing a continuous current were important aids to understanding the connection between electricity and magnetism. Moreover, they suggested the possibility of eventually generating electricity on a large scale. The production of electrical current involves changing energy from one form to another. When electrical energy appears, the law of conservation of energy requires that it be at the cost of some other form of energy. In the electric battery, chemical energy (the energy of formation of chemical compounds) is converted to electrical energy. Batteries are useful for many portable applications (automobiles, computers, cell phones, for example). But it is not practical to produce large amounts of electrical energy by this means. There is, however, a vast supply of mechanical energy available from many sources. Electrical energy could be produced on a large scale if some reasonably efficient means of converting mechanical energy to electrical energy were available. This mechanical energy might be in the form of wind, or falling water, or continuous mechanical motion produced by a steam engine. The discovery of electromagnetic induction showed that, at least in principle, it is possible to produce electricity by mechanical means. In this sense, Faraday can rightly be regarded as the founder of the modern electrical age.

11.4 GENERATING ELECTRICITY: THE GENERATOR

Faraday had shown that when a conducting wire moves relative to a magnetic field, an electric current is produced. Whether it is the wire or the magnetic field that moves does not matter. What counts is the relative motion of one with respect to the other. Once the principle of electromagnetic induction was known, experimenters tested many combinations of wires and magnets in relative motion. One basic type of *generator* (or "dynamo," as it was often called) was widely used in the nineteenth century. In fact, it remains the basic model for many generators today.

This form of generator is basically a coil of wire made to rotate in a steady magnetic field, thereby "cutting" the lines of force, using Faraday's image. The coil is connected to an external circuit by sliding contacts. In Figure 11.5, the "coil" is shown for simplicity as a single rectangular loop of wire. This loop rotates around an axis xy between the north and south poles of a magnet. Two conducting rings, labeled d and e are permanently attached to the loop and, therefore, also rotate around the axis. Conducting contacts, called "brushes," here labeled g and f, complete a circuit through a meter (h) that indicates the current produced. The complete circuit is abdfhgea. (Note that one part of the wire goes through ring d without touching it and connects to e.)

Initially, the loop is at rest between the magnetic poles and no charge flows through it. Now suppose the loop is rotated counterclockwise. The wire's long sides a and b now have a component of motion perpendicular to the direction of the magnetic lines of force; that is, the wire "cuts across" lines of force. This, according to the principle of electric induction, is the condition for inducing an electric current in the loop. The greater the rate at which the lines are cut, the greater the induced current.

To understand better what is going on in the wire, one should understand its operation in terms of the force on the movable charges in the wire. It is the movement of these charges, which are, by convention, assumed to be positive, that forms the current. The charges in the part of the loop labeled b are being physically moved together with the loop across the magnetic field. Therefore, they experience a magnetic force given by qvB (as described in Section 10.11). This force pushes the charges in the wire "off to the side"—that is, perpendicular to both the velocity vector and the magnetic field vector. In this situation, "off to the side" is *along the wire*.

What about side a? It is also moving through the field and "cutting" lines of force, but in the opposite direction. So the charges inside a experience a push along the wire in the direction opposite to those in b. This is just what is needed; the two effects reinforce each other in generating a current around the whole loop. The "push" on the charges that produces the current can also be regarded as resulting from a potential difference ("voltage") induced in the loop of wire. Thus, a generator produces both "voltage" and current.

The generator just described produces *alternating current* (abbreviations AC). The current is called "alternating" because it regularly reverses

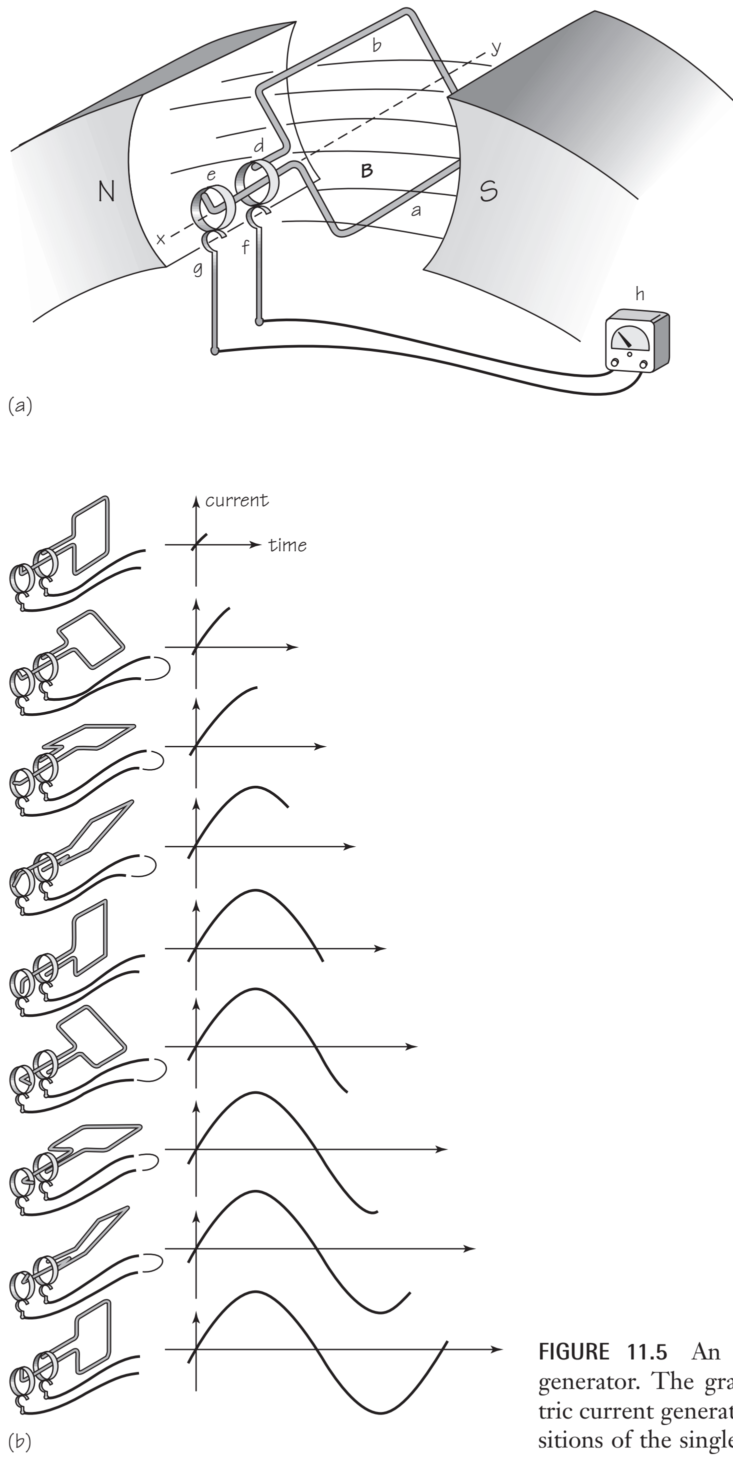


FIGURE 11.5 An alternating current generator. The graph shows the electric current generated as successive positions of the single loop are reached.

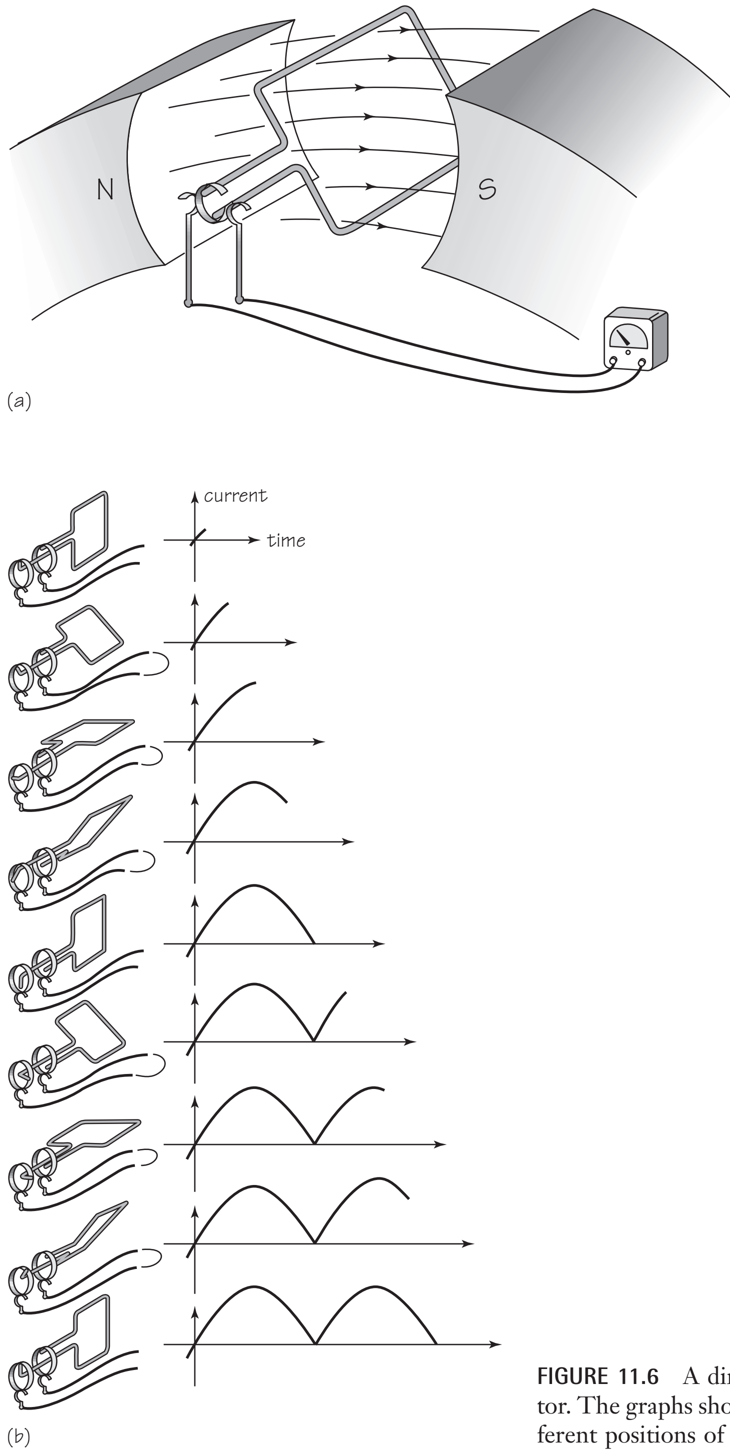


FIGURE 11.6 A direct current generator. The graphs show the current at different positions of the loop.

(alternates) its direction. At the time this kind of generator was first developed, in the 1830s, alternating current could *not* be used to run machines. Instead *direct current* (DC) was needed.

In 1832, Ampère announced that his talented instrument maker, Hippolyte Pixii, had solved the problem of generating direct current. Pixii modified the AC generator by means of a device called the *commutator*. The name comes from the word *commute*, to interchange or to go back and forth. The commutator is a split cylinder inserted in the circuit. In the AC generator, brushes f and g are always connected to the same part of the loop. But with the commutator, the brushes *reverse connections* each time the loop passes through the vertical position. Just as the direction of current induced in the loop is at the point of reversing, the contacts reverse. As a result, the current in the outside circuit is always in the same direction; in short, it is a direct current. Although the current in the outside circuit in that system is always in the same direction, it is not constant. It rises and falls rapidly between zero and its maximum value. In working generators, many sets of loops and commutators are connected together on the same shaft. In this way, their induced currents reach their maximum and zero values at different times. The *total* current from all of them together is then more uniform.

Whether a generator delivers alternating current or direct current, the electric power (energy per unit time) produced at every instant is given by the same equation developed in Section 10.7:

$$P = V \cdot I = I^2R.$$

For example, suppose that a wire (e.g., the filament wire in a light bulb) with resistance R is substituted for the meter at h. If the current generated in the circuit at a given time is I, the electrical energy per unit time delivered to the wire is given by I^2R. For alternating current, the power output varies from instant to instant. But the *average* output power is simply $P = (I^2)_{av}R$. This electrical energy, of course, does not appear by itself, without any source. That would violate the law of conservation of energy. In the generator, the "source" of energy is clearly the mechanical energy which is supplied to keep the coils rotating in the magnetic field. This mechanical energy may be provided by a steam or gasoline engine, or by water power, wind power, or even by human exertion. The electric generator is, in principle, simply a device for converting mechanical energy into electrical energy.

11.5 PUTTING ELECTRICITY TO WORK: THE MOTOR

After the invention of the electric motor in 1873, the greatest obstacle to its practical use was the lack of cheap electric current to run it. The chemical energy in a battery was quickly exhausted. The electric generator,

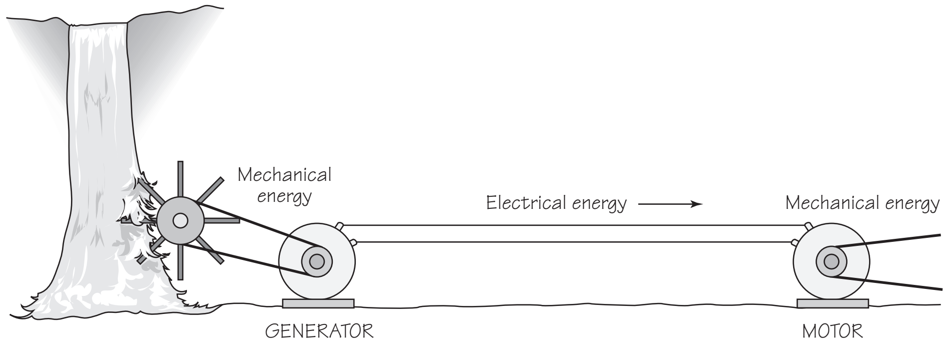


FIGURE 11.7 Generator and motor.

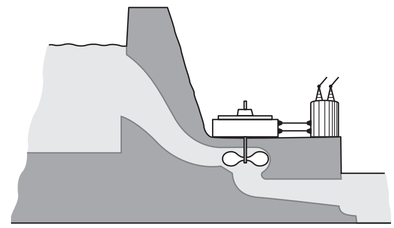
invented almost simultaneously by Faraday and Henry in 1832, was at first not at all economical in producing electrical current when mechanical energy was expended on it. Generators that used mechanical power efficiently to produce electric power were needed. But to design such generators required an understanding of the details of operation, and this understanding took nearly 50 years to acquire.

A chance event marked the effective take-off of the electric power age. This event was an accidental discovery at the Venice Exhibition of 1873. The story goes that an unknown worker at the Exhibition just happened to connect two dynamos (generators) together. The first dynamo, which was mechanically driven, generated current, and this current then passed through the coils of the second dynamo. Amazingly, the second dynamo then ran as an electric motor, driven by the electricity generated by the first dynamo.

The exhibitors at the Exhibition immediately utilized the accidental discovery that a generator run in reverse by the input of current could function as a motor through the output of mechanical work. They used a small artificial waterfall to drive the generator. Its current then drove the motor, which in turn operated a device that did mechanical work. *This, in effect, is the basic operation of a modern electrical transmission system*. A turbine driven, say, by steam or moving water, drives a generator which converts the mechanical energy to electrical energy. Conducting wires transmit the electricity over long distances to motors, toasters, electric lights, computers, etc. These devices in turn convert the electrical energy to mechanical energy, heat, or light.

The steam *turbine*, invented by the English engineer Charles Parsons in 1884, has now largely replaced older kinds of steam engines. At present, steam turbines drive the electric generators in most electric-power stations. These steam-run generators supply most of the power for the machinery of modern civilization. Even in nuclear power stations, the nuclear energy

FIGURE 11.8 The general principle of hydroelectric power generation is illustrated in this sketch. Water flowing from a higher to a lower level turns turbine blades attached to a generator shaft. The details of construction vary widely.



is generally used to produce steam, which then drives turbines and electric generators. (Other means may be used to drive turbines such as wind and water. See Section 11.10.)

The basic principle of the Parsons turbine is simpler than that of the Newcomen and Watt engines. A jet of high-pressure steam strikes the blades of a rotor, driving the rotor around at high speed. The steam expands after passing through the rotor, so the next rotor must be larger. This accounts for the characteristic shape of turbines. Large electric-power station turbines using more than 500,000 kg of steam an hour can generate electrical energy at a rate greater than one billion joules per second.

The development of electrical generators shows an interaction of science and technology different from that of the development of steam engines. As was pointed out in Chapter 7, the early steam engines arose from the efforts of practical inventors. These inventors had no knowledge of the current theory of heat (thermodynamics). But their development of the steam engine, and attempts by Sadi Carnot and others to improve its efficiency through theoretical analysis, contributed greatly to the establishment of

FIGURE 11.9 Power station with a set of water-driven electric generators.

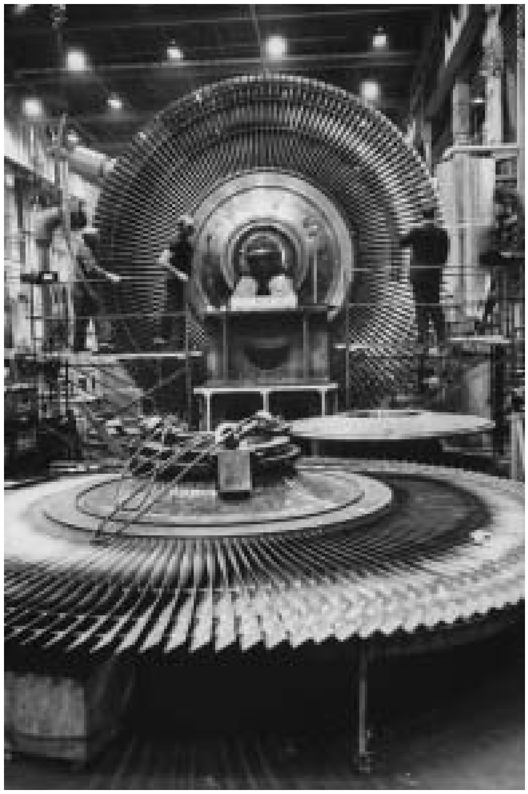


FIGURE 11.10 Steam turbine rotors.

thermodynamics. In that case, the advance in technology came before the advance of science. In the case of electromagnetism, the reverse occurred. Ampère, Faraday, Kelvin, Maxwell, and others had built up a large amount of scientific knowledge before any serious practical application succeeded. The scientists, who understood electricity better than anyone else, were not especially interested in commercial applications. And the inventors, who hoped to make huge profits from electricity, knew very little scientific theory. After Faraday announced his discovery of electromagnetic induction, people started making generators to produce electricity immediately. But it was not until decades later that inventors and engineers understood enough to work with such necessary concepts as lines of force and field vectors. With the introduction of the telegraph, telephone, radio, and alternating-current power systems, a much greater mathematical knowledge was needed to work with electricity. Universities and technical schools started to give courses in electrical engineering. Gradually, a group of specialists developed who were familiar with the physics of electricity and who also knew how to apply it.

11.6 THE ELECTRIC LIGHT BULB

The enormous growth of the electrical industry resulted from the great public demand for electrical products. One of the first commercially successful electrical products was the electric light bulb, which brought the benefits of electricity to the general public and made electricity the dominant form of early private energy consumption. The success of the light bulb mirrors in some respects the success of such other technological inventions as the microchip or television. It is an outstanding case study of the relationship between physics, industry, and society.

At the beginning of the nineteenth century, most buildings and homes were lit by candles and oil lamps. It is said that, during his school years, Abraham Lincoln did most of his reading by the fireplace. There was almost no street lighting in cities except for a few lamps hung outside houses at night. The natural gas industry was just starting to change this situation. London got its first street lighting system in 1813, when gas lights were installed on Westminster Bridge. However, the social effects of gas lighting were not all beneficial. For example, gas lighting in factories enabled employers to extend an already long and difficult working day into one still longer.

As the British chemist Humphry Davy and other scientists showed, light can be produced simply by heating a wire to a high temperature by passing a current through it. This method is known as *incandescent* lighting. The major technical drawback here was that the wire filament gradually burned up. The obvious solution was to enclose the filament in a glass container from which all the air had been removed. But this was easier said than done. The vacuum pumps available in the early nineteenth century could not produce a strong enough vacuum for this purpose. It was not until 1865, when Hermann Sprengel in Germany invented an improved vacuum pump, that the modern electric light bulb became possible. (Sprengel's pump also greatly aided Crookes and others in scientific experiments leading to important discoveries in atomic physics. These discoveries will be discussed in Chapter 13.)

Thomas A. Edison was not the first to invent an incandescent light, nor did he discover any essentially new scientific principles. What he did was to develop a practical light bulb for use in homes. Even more important, he worked out a distribution system for electricity. His system not only made the light bulb a practical device, but it opened the way for mass consumption of electrical energy in the United States.

Edison started by making an important business assumption about *how* people would want to use their light bulbs. He decided that each customer

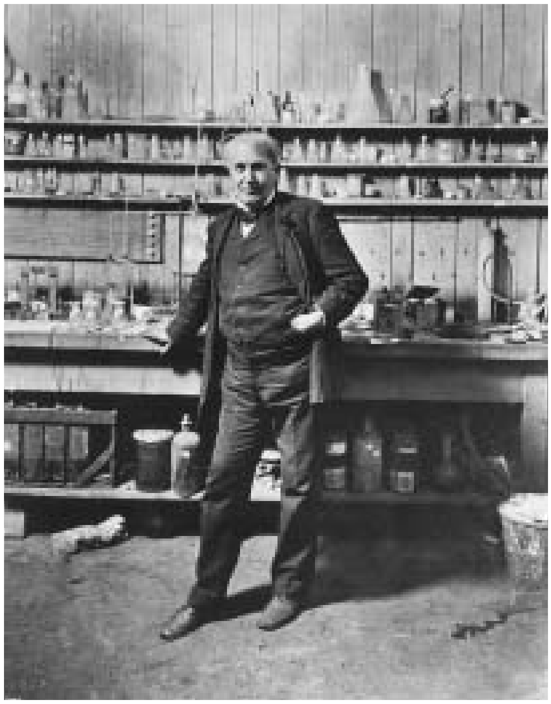


FIGURE 11.11 Edison in his laboratory.

must be able to turn on and off any single bulb without affecting the other bulbs connected to the circuit. This meant that the bulbs must be connected "in parallel," like the rungs of a ladder, rather than "in series." (See Figure 11.13.)

The choice of parallel rather than series circuits had important technical consequences. In a series circuit, the same current goes through each bulb. In a parallel circuit, only part of the total current available from the source goes through any one bulb. To keep the total current needed from being too large, the current in each bulb has to be small.

As noted in Section 10.7, the heating effect of a current depends on both the resistance of the wire and the amount of current. The rate at which heat and light energy are produced is given by $P = I^2R$. According to this relationship, the rate goes up directly as the resistance, but increases as the *square* of the current. Therefore, in order to produce more light, most inventors used high-current, low-resistance bulbs and assumed that parallel circuits would not be practical. Edison realized that, in addition to the practicality of parallel circuits, a small current can have a large lighting effect if the resistance is high enough.

So Edison began a search for a suitable high-resistance, nonmetallic substance for his light-bulb filaments. To make such a filament, he first had to

FIGURE 11.12 Lewis Howard Latimer (1848–1928), the son of an escaped slave, became one of the original associates of Thomas Edison. Latimer was an inventor, patent authority, poet, draftsman, author, and musician.

bake or "carbonize" a thin piece of a substance. Then he sealed it inside an evacuated glass bulb with wires leading out. His assistants, including Lewis Howard Latimer, tried more than 1600 kinds of material:

> paper and cloth, thread, fishline, fiber, celluloid, boxwood, coconut shells, spruce, hickory, hay, maple shavings, rosewood, punk, cork, flax, bamboo, and the hair out of a redheaded Scotchman's beard.

Edison made his first successful high-resistance lamp in October 1879 with carbonized cotton thread in a high-vacuum sealed bulb. It burned continuously for 2 days before it fell apart. The following year, Edison produced lamps with filaments made from bamboo and paper. The Edison Electric Light Company began to install lighting systems in 1882. After only 3 years of operation, the Edison company had sold 200,000 lamps. It had a virtual monopoly of the field and paid big dividends to its stockholders.

The electric light bulb has changed somewhat since Edison's original invention. For example, the carbonized filaments of the older lamps were replaced in newer bulbs by thin tungsten wires. Tungsten had the advantages of greater efficiency and longer life.

The widespread use of light bulbs confirmed the soundness of Edison's assumptions about what people would buy. It also led to the rapid development of systems of power generation and distribution. The need for more power for lighting spurred the invention of better generators, the harnessing of water power, and the invention of the steam turbine. Success in providing large quantities of cheap energy made other uses of electricity practical. Once homes were wired for electric lights, the current could be used to run sewing machines, vacuum cleaners, washing machines, toasters, and (later on) refrigerators, radios, television sets, and computers. Once electric power was available for public transportation, cities could grow rapidly in all dimensions. Electric elevators made high-rise buildings practical,

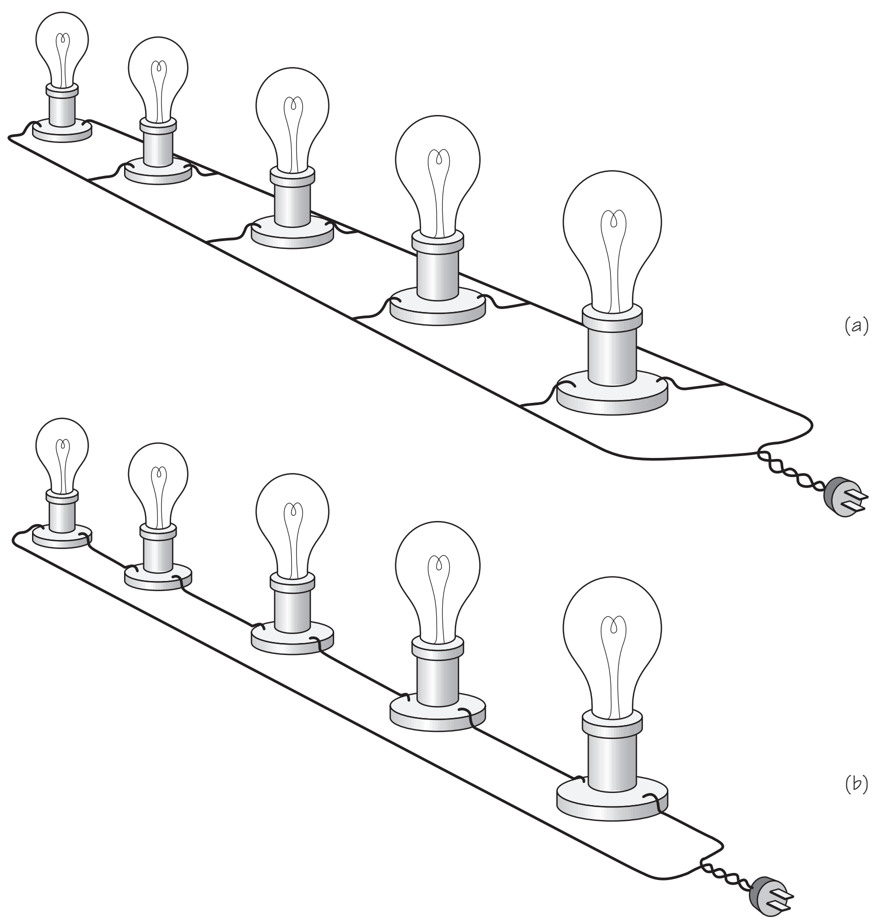
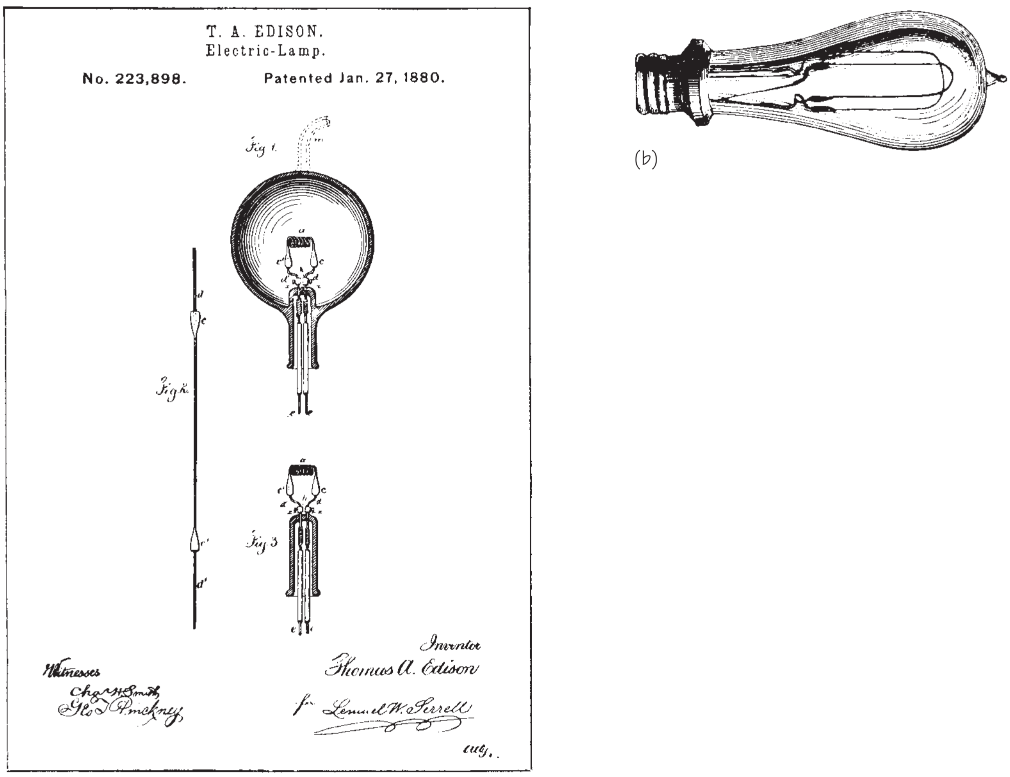


FIGURE 11.13 (a) Bulbs in a parallel circuit; (b) bulbs in a series circuit.



(a) (b)

FIGURE 11.14 Two drawings of Edison's invention.

while electric tramways and subways rapidly transported people from their homes to jobs and markets.

We are now so accustomed to more sophisticated applications of electricity that it is hard to realize the impact of something as simple as the light bulb. But most people who lived through the period of electrification, which was as late as the 1930s and 1940s in many rural areas of the United States, agreed that the electrical appliance that made the greatest difference in their lives was the electric light bulb, which made the evenings fit for finishing chores indoors, as well as for leisure activities or reading. The last was one of the reasons given by President Franklin D. Roosevelt for his interest in promoting large-scale rural electrification, as in the Tennessee Valley Authority (TVA). In addition, of course, electric machines have been able to lighten many heavy physical labors and to make possible work that human or animal strength could never have accomplished.

11.7 AC VERSUS DC: THE NIAGARA FALLS POWER PLANT

Section 11.4 stated that the earliest electric generators produced alternating current (AC), which could be changed into direct current (DC) by the use of a commutator. Throughout most of the nineteenth century, most engineers believed that only DC was useful in practical applications of electricity. However, as the demand for electric power increased, some disadvantages of DC became evident. One problem was that the commutator complicated the mechanical design of generators, especially if the ring had to rotate at high speed. This difficulty became even more serious after the introduction of steam turbines in the 1890s, since turbines work most effectively at high speeds. Another disadvantage was there was no convenient way of changing the generated voltage of a DC supply.

Why should it be necessary to change the voltage with which current is driven through a transmission system? One reason involves the amount of power lost in heating the transmission wires. The power output of a generator depends (as indicated in Section 10.8) on the output *voltage* of the generator and the amount of *current*:

$$P_{\text{total}} = VI.$$

The power made available by the generator is transmitted to the line and to the consumer. (For this reason, commercial power is often given in units of volt-amps.) The same amount of power can be delivered at smaller I if V is somehow made larger. As noted in Section 10.7, when there is a current I in a transmission wire of resistance R, the portion of the power lost as heat in transmission is equal to the resistance times the square of the current:

$$P_{\text{heat loss}} = I^2R.$$

The power finally available to consumers is $P_{\text{total}} - P_{\text{heat loss}}$. For transmission lines of a given resistance R, where the value of R is fixed by the wires themselves, the current I should be as small as possible in order to minimize the power loss. Obviously, therefore, electricity should be transmitted at low current and at high voltage.

However, most generators cannot produce electricity at very high voltages. To do so would require excessively high speeds of the moving parts. Some way of "stepping up" the generated electricity to a high voltage for transmission is needed. But some way of "stepping down" voltage again at

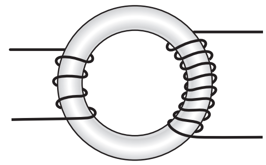


FIGURE 11.15 Transformer coils.

the other end, where the consumer uses the power, is also needed. For most applications of electricity, especially in homes, it is neither convenient nor safe to use high voltages. In short, *transformers* are needed at both ends of the transmission line.

A transformer can easily be made by a simple change in Faraday's induction coil (Section 11.4). Recall that Faraday wound a coil of wire—called the *secondary* coil—around one side of an iron ring. He then induced a current in this secondary coil by changing a current in another coil—the *primary* coil—wound around the other side of the ring. A current is induced in the secondary coil whenever the primary current changes. If the primary current is changing all the time, then a current is continually induced in the secondary. An AC applied to the primary coil (e.g., from a generator without a commutator) induces an AC in the secondary coil.

After the American engineer George Westinghouse saw an AC electrical system in Italy he bought the American patent rights for it. When the

FIGURE 11.16 The commercial distribution of AC electric power requires elaborate transmission facilities. Generator output voltages of about 10^4 volts are stepped up to about 10^5 volts for transmission, stepped down to about 10^4 volts for local distribution, and further stepped down to about 10^2 volts by neighborhood power-pole transformers. Within the home, they may be stepped down further (often to 6 volts for doorbells and electric trains) and stepped up by transformers in radio and TV sets for operating high-voltage tubes.

FIGURE 11.17 Dam on Niagara River.

Westinghouse Electric Company introduced the AC system to the United States with improved transformers in 1886, the Edison Electric Light Company (which later merged into General Electric) already had a monopoly on electric lighting and had already invested heavily in DC generating plants and distribution systems for most of the large cities. A bitter public controversy erupted between the two companies. Edison attempted to show that AC was unsafe because of the high voltage (tension) used for transmission in "high-tension" wires. In the middle of the dispute, the New York State legislature accepted Edison's suggestion of electrocution as a means of capital punishment. This event seems to have added to the popular fear of high voltage. Nevertheless, Westinghouse's AC system continued to grow. There were no spectacular accidents, and the public began to accept AC as reasonably safe.

The final victory of the AC system in the United States was assured in 1893 when businessmen in Buffalo, New York, chose AC for the new hydroelectric plant at Niagara Falls. It was a close decision. AC could be generated and transmitted more efficiently, but the demand for electricity in 1890 was mainly for lighting. This meant that there would be a peak demand in the evening. The system would have to operate at less than full capacity during the day and late at night. Because of this variation, some engineers believed that a DC system would be cheaper to operate. However, European systems began demonstrating that this was not the case, and expert opinion gradually changed in favor of AC over DC. Today, electric power in the United States is delivered to homes and factories in an AC that alternates at a frequency of 60 cycles per second, or 60 Hz. Most of the rest of the world uses AC current at 50 Hz.

It turned out that the critics had been wrong about the variation of demand for electricity throughout the day, as electricity found many uses besides lighting. During periods of lower demands, hydroelectric plants often use their excess capacity to store energy by pumping water up into reservoirs. The potential energy thus created can be used later to produce electricity during periods of peak demand as the potential energy is converted back into mechanical energy to run the generators. (We return to hydroelectric power in Section 11.10.)

11.8 THE ENERGY PICTURE TODAY

The average human being requires in his or her nutrition about eight million joules, or 2000 Calories, of energy for an average work day. (Nutrient labels required on all food packaging are based on an assumed diet of 2000 Calories, which is 2000 kcal.) This is roughly equivalent to the energy output of a 100-W light bulb burning for 24 hr. For millions of years the average daily consumption of energy per person on this planet remained at this amount. Then, about 10,000 years ago, the amount of energy use began to rise with the establishment of empires, the domestication of animals for work in agriculture, and the introduction of machines—all of which consumed additional energy. Energy consumption has risen steadily ever since, until today the amount of energy consumption per day, averaged over the world's population, is about one billion joules per person per day—over one hundred times the subsistence level. This figure is even more astounding when we realize that the number of people on Earth has also increased dramatically, and that most of those people do not live in energy-intensive industrial societies. The world population today is about six billion people, compared with only about one million people 10,000 years ago.

What are these billions of joules of energy per day used for, and where do they come from? Of course, the picture differs from nation to nation and between industrial and developing nations. We focus here on the United States economy, which, according to recent estimates, consumes about 85×10^{18} J of energy per year—or about one hundred billion joules per person per day. The table below shows the distribution of this energy and its usage by each sector of the United States economy in the mid-1990s.

Distribution of Energy Usage in the United States Economy in Units of 10^{18} J

Sector of economy	*Useful work and heating*	*Wasted energy*	*Total energy consumed*
Industrial	12	12	24
Residential and commercial	12	5	17
Transportation	5	19	24
Power generation and transmission	*	20	20
Column total	29	56	85
Percent of total energy	34%	66%	100%

* 10×10^{18} J for this purpose were included above in the useful energy consumed by the *industrial* and *residential/commercial* sectors.

Derived from A. Hobson, *Physics: Concepts and Connections* (Englewood Cliffs, NJ: Prentice-Hall, 1999), p. 448.

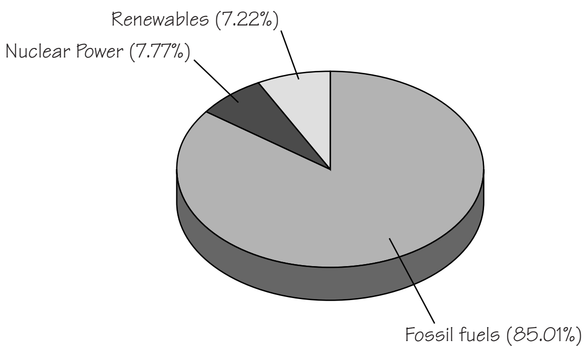
The table indicates that nearly two-thirds of the energy consumed in the United States is wasted. This waste arises not only from careless use of the energy provided, but also in large part from the restrictions on the efficiencies of heat engines owing to the second law of thermodynamics. The impact of the second law is greatest in the transportation and power generation sectors of the economy, which rely heavily on heat engines. For instance, the transportation sector, which displays the lowest energy efficiency (20.8%) of the above sectors of the economy, is dominated by the internal combustion engine. The average automobile cruising without acceleration at the most efficient highway speed (55 mi/hr) has an energy efficiency of only about 13%; that is, of the 70 kW of energy obtained from the fuel tank, 61 kW are unused in some fashion and only 9 kW are converted into the useful work needed to overcome air resistance and rolling resistance. Highway speeds above 55 mi/hr yield significantly lower efficiencies for such vehicles. Sport utility vehicles and light trucks, which currently represent a large fraction of new private passenger vehicles, have even lower overall efficiencies than automobiles. (Heat-engine efficiencies are further discussed in the next section.)

Energy Resources

Where does the energy consumed come from? The pie graph and table on next page show the main sources of energy in the United States and their percentage contributions to the economy (as of 2000). (Following the categories used by the Department of Energy, "renewables" include all sources other than fossil fuels and nuclear power.)

Energy Sources for the United States Economy, 2000

	Percent
Fossil Fuels	
Crude oil	35.2
Coal	27.9
Natural gas	19.4
Natural gas from plant liquid	2.52
Nuclear Power	7.77
Renewables	
Hydroelectric	3.25
Wood and biomass	3.53
Geothermal	0.33
Solar	0.076
Wind	0.038



Source: US Dept. of Energy, http://www.eia.doe.gov/emeu/aer/overview.html

As you can see, 85% of the nation's energy needs are provided by three fossil fuels—oil, coal, and natural gas—in which chemical energy from the remains of organisms that lived millions of years ago is stored. The remaining 15% is provided by nuclear power and renewables. All of the nuclear and hydroelectric power and most of the coal is used for the production of electricity through steam-powered generators. Some of the oil and natural gas is also used for this purpose, especially in the Northeast, where it is easier and cheaper to import natural gas and oil, e.g., from Canada, than it is to ship coal from the Midwest. However, all of the wood and most of the oil and natural gas are used for nonelectric purposes—wood and gas for heating, oil for transportation.

While the United States is heavily dependent upon fossil fuels for its energy needs, the outlook is not promising. Some analysts have pointed out that industries in the more developed nations have used up in 200 years most of the reserves of chemical energy accumulated over the last 200 *million* years. According to current estimates, the world's remaining supply of coal will last only about another two centuries at the current rate of usage, while the estimated remaining supply of oil will last only another 50 years or so at the current usage rate. If such estimates are accurate, they indicate that we cannot continue the current energy scenario much longer. For example, the United States is over 50% dependent on imported energy sources, but many of the reserves are in politically unstable regions. Developing nations are demanding an increasing share of the fossil fuels in order to attain the benefits of industrialization for their economies. And the burning of fossil fuels is contributing to pollution and to significant climate change through the greenhouse effect leading to global warming. This is further discussed in Section 12.5.

11.9 CONSERVATION

Nuclear energy was once thought to be the answer to our increasing energy needs, and it may well be in the future—especially considering the urgency of supplying energy for commercial use. However, in the wake of the Three Mile Island and Chernobyl accidents and in view of the possibility of a terrorist attack on nuclear reactors, the American public has turned against nuclear energy, and federal regulators have not renewed the licenses of reactors located near densely populated areas. All active construction of new fission reactors has ceased in the United States, often at great losses to the utility companies (which have shifted the losses to their consumers through higher rates). Although there is only a little air pollution (not radioactive) from nuclear reactors, there is the problem of heat pollution as well as radioactive waste. All of the equipment, spent fuel rods, water, and even the clothing of the workers are radioactive and must be safely stored for thousands of years (until several half-lives of the radioactive elements involved have passed). These problems have both a technological as well as a political component, and until these can be resolved, fission reactors will probably not be the long-term solution to this nation's energy needs. As further discussed in Chapter 18, fusion energy, which would have none of the problems of present-day nuclear reactors, is not yet a practical reality, but it may well be in the years ahead.

> Note that other industrial nations, in particular France and Japan, rely heavily on nuclear energy for their electrical needs and continue to build new plants.

With nuclear energy not a long-term solution for the United States at this time, there are at least two other ways in which the United States,

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which currently has the largest economy and the greatest total energy consumption on Earth, can provide for its long-term energy needs:

- conservation of energy through reduction of energy losses;
- the opening of renewable and other alternative sources of energy.

As with the steam engine and the early electric age, the problem of energy usage is primarily a scientific and technological one, but the fundamental decisions are ultimately made by the public through their representatives and, especially, through individual consumer choices. (Increasing production of crude oil or natural gas from national reserves cannot be a long-term solution.)

Efficiency of a Power Plant

An electric power plant, whether powered by fossil fuels (coal, oil, or gas) or nuclear fuel, needs both a heat engine and a generator in order to produce electricity. The thermodynamic limit of the efficiency of a heat engine sets very severe constraints on how much of the energy released from burning the fuel is ultimately available as electrical energy. (This limit does not, of course, apply to hydroelectric plants.)

As discussed in Section 6.3, any engine that converts heat into mechanical work must also release heat into the environment. A diagram of this process, which can be applied to Watt's steam engine or to a large steam turbine, is sketched in Figure 11.18. T_1 and T_2 are the temperatures of the hot and cold reservoirs, respectively; Q_1 is the heat fed into the engine; Q_2 is the waste heat released into the environment; and W is the useful mechanical work obtained from the engine.

The second law of thermodynamics states that in the best possible circumstances the efficiency (eff) of the heat engine can be no greater than

$$\text{eff} = 1 - \frac{T_1}{T_2}.$$

This law is discussed in detail in Section 6.3.

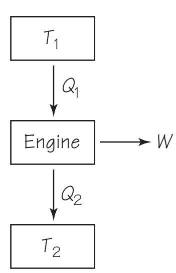

FIGURE 11.18 Block diagram of physical quantities in the operation of a heat engine.

What does this mean for a power plant? Fuel is burned in a combustion chamber, the chemical (or nuclear) energy is converted into thermal energy that keeps the combustion chamber at the temperature T_1. Water, heated by the combustion chamber in the boiler, circulates through the plant as steam during parts of its route and as liquid during others. In most plants, very high-pressure steam is created in the boiler. This steam pushes against the blades of a turbine, doing work on the turbine, and leaves the turbine as steam at a much lower pressure and temperature. The electric generator converts the mechanical work done on the turbine into electric energy; this process is not restricted by the second law because no thermal energy is involved. Finally, the steam must be condensed so that the water can retrace its route through the plant. This is done by allowing heat Q_2 to escape to the environment at temperature T_2. The whole process is shown schematically in Figure 11.18.

For the best efficiency (as close to 1 as possible), T_2 should be as low as possible, and T_1 as high as possible, so that T_2/T_1 is as small as possible. However, T_2 is fixed by the environment, since cooling air or water must be used at whatever temperature is available outside. This is generally about 20–25°C (about 300 K). T_1 is limited by technology and chemistry. Metals weaken and melt when they get too hot. For a modern fossil-fuel plant, T_1 may be as high as 500°C (about 770 K). In a nuclear power plant, caution suggests more conservative limits, and therefore T_1 is typically 400°C (about 670 K). The lower temperature is necessary, in particular, to avoid damaging the fuel rods.

The maximum possible efficiencies of fossil-fuel and nuclear-power plants is thus

$$\text{eff} = 1 - \frac{T_2}{T_1} = 1 - 300/730 \simeq 0.59 \quad \text{(fossil-fuel plant)}$$

$$= 1 - 300/670 \simeq 0.55 \quad \text{(nuclear-power plant)}$$

(The sign $\simeq$ means "approximately equal to.") Therefore, *even if there were no losses of any kind whatsoever*, a power plant could only turn about half of the thermal energy into electrical energy. For each joule of electrical energy produced, 2 J of energy will have to be provided originally by the fuel. The remaining joule will be released to the environment (into a river, the ocean, or the air) as thermal pollution.

The preceding paragraph describes the maximum possible efficiency of a perfect Carnot engine. Real power plants are significantly less efficient. Modern fossil-fuel plants can achieve about 38% or 40% in practice; nuclear plants, because of the lower value of T_1, can manage about 30%. Older fossil plants have efficiencies of 30% or less. These additional losses are

FIGURE 11.19 The Hong Kong skyline at night.

due to the fact that turbines are not ideal Carnot engines (they have friction; some heat simply leaks through them without doing any work at all) and to the fact that there are losses in generators, transformers, and power lines. A useful rule of thumb is that the overall efficiency of a power plant is about 33%.

What this analysis shows is, very roughly, that any time you use 1 J of electrical energy, about 3 J of thermal energy were produced at the power plant, and 2 J were released into the environment, mostly near the plant. For example, if you heat a room with a small electric heater, about three times as much fuel has to be burned to produce the needed energy when the same fuel is burned directly within the room itself (in a gas stove, for example). Through state and federal incentive programs, some progress is being made in convincing consumers to buy, and manufacturers to produce, more energy-efficient appliances. But this cannot significantly reduce the overall waste of energy in electrical production and transmission. This is the trade-off for the fact that electricity is such a convenient source of power. Only new technologies and discoveries can make a major difference in reducing this waste.

Because it is largely a consumer decision, the reduction of waste in the area of transportation may occur more readily. Transportation as a whole accounts for about 70% of the crude oil consumed in the United States

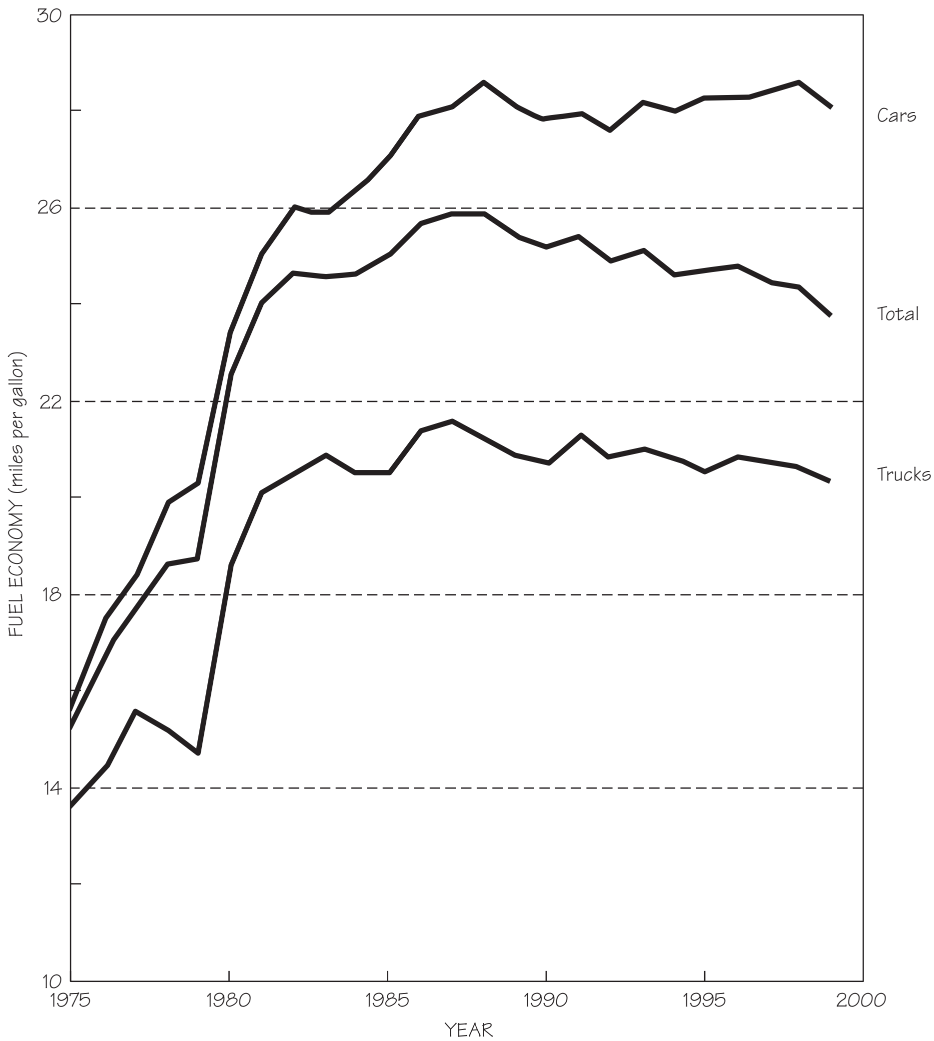

FIGURE 11.20 Average gas mileage of U.S. vehicles over time (at moderate highway speed).

and for about one-third of the total energy lost. The fuel efficiency of automobiles is controlled by technology, as discussed earlier, but advances in technology are strongly driven by consumer choice. On this point the track record in the United States has been spotty at best. Automobile efficiency began to go up following the oil crisis of the mid-1970s, when the public supported improvements in fuel efficiency and conservation. The picture changed beginning in the mid-1980s, when gas prices turned far lower than those in any other industrial nation, and when conservation became less

TWO AMERICAN TECHNOLOGIES

Telephone Technology

The word telephone comes from the Greek roots *tele*, "far," and *phone*, "sound." It was used as far back as the seventeenth century to refer to the communication device using a string with a mouthpiece and hearing devices at either end. However, in its modern use it refers to the invention by the Scottish-born American inventor Alexander Graham Bell.

Bell had a lifelong preoccupation with speech and communication, and while professor of "Vocal Physiology and Elocution" at Boston University, he began work on a machine that would transmit the voice along electric wires. In 1875, drawing on Hans Christian Oersted's and Michael Faraday's work on electromagnetism, Bell placed a metal diaphragm near an electromagnet; and then used the sound of a human voice to vibrate the diaphragm, which in turn changed the magnetic field, thus inducing a varying current.

The following year Bell improved on this model by placing a wire in mercury, which could be used in a circuit to vary resistance and therefore produce an undulating current when vibrated by a voice. In March 1876, in Boston, MA, Watson heard from the device Bell saying in the next room, "Mr. Watson, come here. I want to see you."

Bell received patent no. 174,465 for the development of this device to transmit speech sounds over electric wires, which is said to be one of the most valuable patents in history. Over the next few years, Bell was lionized as the inventor of the telephone. In tribute, all telephone service was suspended for a minute during his burial.

Automobile Technology

By 1910, America had overtaken Europe as the leading producer of automobiles. The most successful of this first generation of American automobile manufacturers was Henry Ford, who opened his first plant in 1903 in Detroit, Michigan. The automobile industry was competitive, and the main reason Ford succeeded where others failed seems to have been his central objective to manufacture quality automobiles at a price which the average American family could afford.

With low cost–high quality in mind, Ford introduced the Model T in 1908, which could be purchased at the time for $825, with the advertising claim "No car under $2000 offers more, and no car over $2000 offers more except the trimmings." In 1910 Ford opened the Highland Park assembly plant, which was a 60-acre site in Detroit. Continuous conveyor belts were introduced at this plant in 1912, and moving assembly lines in 1913. These methods of mass production enabled Ford to reduce the cost of the Model T further by more than half, while increasing the number of units produced. Not only did these methods of mass production help to increase the standard of living of the average American family, but with the introduction of the (then remarkable) 8-hour day into his plants, Ford also increased the demand for his motorcars by increasing factory workers' pay and leisure time.

Further Reading

R.V. Bruce, Alexander Graham Bell and the Conquest of Solitude, In: C.W. Pursell, Jr., ed., *Technology in America* (Cambridge, MA: MIT Press, 1989), pp. 105–116.

J.J. Flink, Henry Ford and the Triumph of the Automobile, In: C.W. Pursell., Jr., ed., *Technology in America* (Cambridge, MA: MIT Press, 1989), pp. 172–173.

popular. At that point the United States began to grow even more dependent on imported oil from the Middle East and elsewhere, imported oil now exceeding 50% of total crude-oil consumption. During the same period, the average fuel usage calculated for all automobiles remained constant at about 25 miles per gallon, while the amount of gasoline used increased owing to more driving.

The picture changed for the worse during the 1990s with the popularity of less efficiency sport utility vehicles (SUVs), the low prices for gas during that decade, and a general public apathy about conservation efforts. Some states have passed laws requiring at least a minimum number of "zero emission vehicles" on the road by the year 2010. At present, manufacturers and the government are devoting increased financial resources to research and development of battery-operated cars, buses, and trucks as well as hybrid (electric and internal combustion) vehicles.

11.10 RENEWABLE AND ALTERNATIVE ENERGY SOURCES

Electric generators are not the only means of producing electricity, nor is electricity the only means of producing heat and light. The burning of wood, coal, and even oil and gas can produce rudimentary heat and light without electricity, as does the use of solar heating. In solar heating, direct sunlight is used to light and warm buildings during the day. It is also used to heat coils of water on buildings. The heated water is then circulated into a building to provide heat as well as hot water. More indirectly, solar power is also used to grow foodstuffs, which of course is also an essential source of energy for us.

Solar power is receiving intense study as a means of producing electricity because of the vast amount of energy potentially available. Just outside the Earth's atmosphere the Sun's radiation provides 1360 W of power to each square meter of surface. By the time the radiation reaches the Earth's surface, much of it is lost, because of atmospheric absorption and clouds. Since the Earth rotates, more or less direct sunlight is available in any particular spot on the Earth's surface for only about 8 hr (on the average) each day. Depending upon the location, then, between 150 and 450 W/m^2 are delivered to ground level when averaged over a 24-hr period. This power can be used to boil water with which to power an ordinary steam turbine generating plant, or to heat water for household use.

Sunlight can also be converted directly into electricity in photocells or "solar" cells by a process called *photovoltaic conversion*. The basic operation

FIGURE 11.21 Major electric transmission lines in the continental United States.

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FIGURE 11.22 Solar energy collectors in the Mojave Desert of California.

of the photocell is explained in Chapter 16. Such devices are used today mostly to power individual buildings, pocket calculators, and satellites in outer space. However, even in the best photocell is unable to turn all the energy that strikes it into electrical energy, for much of the light is reflected, transmitted, or turned into wasted heat within the cell.

When solar power could solve many of the problems resulting from fuel shortages and avoid the environmental pollution of other energy sources, the generation of even a significant fraction of our nation's electric power directly from the Sun is dependent on finding ways of building far less expensive collection systems for accepting the Sun's energy, and storage systems for providing the electricity when it is needed (at night, for example, or on cloudy days). Probably the most widely practiced use of solar energy will remain for the foreseeable future at the local level—the heating of houses and the production of hot water for home use.

One of the most attractive alternative energy sources for electricity generation is *wind energy*, the kinetic energy of moving air set into motion by the effects of solar energy on the Earth's atmosphere. The energy in the wind can generate electricity by turning the blades of a propeller attached to an electric generator. Such devices are being used to provide the elec-

FIGURE 11.23 Wind turbines in California for generating electricity.

tricity for cities such as San Jose, California, through the turning of a vast array of propeller-driven generators (wind turbines) in a mountain pass outside the city. Such arrays could also be used successfully in other windy areas of a country, supplying a fraction of the energy needs in those regions. However, winds are never steady and some regions of the nation do not have sufficient winds to generate much electricity. Moreover, some people regard the sight of large arrays of wind turbines across the countryside as a blight upon the landscape. In addition, measures must be taken to keep birds away from the spinning propellers. Thus, while wind energy offers the possibility of large-scale energy production for local use, its prospects at this time are limited as a large-scale commercial source of energy.

Another means of providing the work necessary to turn the coils in an electric generator is to use the potential energy of falling water in a *hydroelectric power* plant. As discussed earlier (Section 11.7), water from a dam or a water fall flows over the blades of a crank shaft connected to a turbine, turning the kinetic energy of the water into the mechanical work necessary to generate electric current. In this way, the Niagara Falls power plant discussed earlier, as well as the Hoover Dam and others, provide

FIGURE 11.24 The out-flow end of water-driven electric generators producing power at Wilson Dam (part of the Tennessee Valley Authority). The plant can generate electric energy at a rate of over 100,000,000 watts.

enormous amounts of hydroelectric power. However, also like wind energy, hydroelectric power is limited only to regions of the country near such a dam or a water fall. In addition, there are often important environmental effects caused by the damming of a river: the impounding of nutrient-rich sediments that are denied to downstream marine life; the disruption of bird or fish migrations, such as the return of salmon to upstream spawning grounds; and the destruction of scenery. Because of the practical and environmental shortcomings, hydroelectric power still accounts for only about 3.25% of this nation's total energy needs.

Strange as it may seem, at present the only other means of providing the mechanical work necessary to turn the crank in a generator is to make use of steam-engine technology—using heat to boil water to produce steam that performs the work necessary to generate an electric current. As noted earlier, the burning of fossil fuels—coal, oil, and natural gas—is still the most widely used means of heating water to produce the steam. But there are at least four other possible heat sources—again, all with significant disadvantages. These alternatives are:

- geothermal energy—tapping the heat inside the Earth arising from geological pressure and radioactive decay;
- biomass energy—the heat released in the chemical breakdown of organic materials, such as wood, compost heaps, and garbage;
- solar-thermal energy—focusing the Sun's rays to heat water to produce the necessary steam (discussed above);
- nuclear energy—using the heat produced in nuclear fission to boil water (Section 11.5, further discussed in Chapter 18).

The first three of these alternatives, as well as wind and hydroelectric power, are classified as *renewable energy sources*. In contrast, fossil fuels and nuclear fission are not renewable, because there is only a limited supply of these resources. When they are used up, they're gone forever. The dilemma is that while the renewable sources involve less pollution and will not be depleted in the near term, they cannot yet supply our total energy need. Moreover, all forms of energy conversion have economic and/or environmental consequences.

In the end, the energy problem will have to be solved through partnership comprising scientific research and technology community and the

FIGURE 11.25 Geothermal power plant in Iceland.

public. The balance among these three can change very rapidly. New breakthroughs, such as the harnessing of fusion energy, may be expected, and new demands by the public expressed through voting patterns and consumer choices can always lead to new choices for our energy needs and our energy future.

FURTHER READING

M. Brower, *Cool Energy: Renewable Solutions to Environmental Problems* (Cambridge, MA: MIT Press, 1992).

R. Rhodes and D. Bollen, The Need for Nuclear Power, *Foreign Affairs*, Jan./Feb. 2000, 30–44.

SOME NEW IDEAS AND CONCEPTS

AC current
commutator
conservation
DC current
electromagnetic induction
fossil fuels
generator
high-tension wire
incandescent lighting
lines of force
motor
parallel circuit
photovoltaic conversion
renewable energy sources
series circuit
transformer
turbine
wind turbine

STUDY GUIDE QUESTIONS

11.1 Transporting Energy from One Place to Another

1. What were some of the deficiencies of the steam engine? In what general way might they be remedied?

11.2 Faraday's First Electric Motor

1. Why does the magnetic pole of Faraday's "electromagnetic rotator" move in a circle around a fixed wire?

11.3 The Discovery of Electromagnetic Induction

1. Why is Faraday considered the discoverer of electromagnetic induction?
2. What is the general definition of electromagnetic induction?

11.4 Generating Electricity: The Generator

1. What is the position of a rotating loop when it generates maximum current? minimum current? Why?
2. What is the purpose of the commutator?
3. Where does the energy delivered by the generator come from?

11.5 Putting Electricity to Work: The Motor

1. How does interaction between science and technology differ in the development of electrical technology from the development of steam-engine technology?
2. How would you make an electric motor out of a generator?
3. What prevented the electric motor from being an immediate economic success?
4. What chance event led to the beginning of the electric power age?

11.6 The Electric Light Bulb

1. What device was essential to the development of the incandescent lamp?
2. Why did Edison require a substance with a high resistance for his light-bulb filaments?
3. What were some of the major effects the introduction of electric power had on everyday life?

11.7 AC versus DC: The Niagara Falls Power Plant

1. What were some of the disadvantages of DC generation?
2. What factors made Edison's recommendation for the use of DC for the Niagara Falls system less attractive?
3. Give one reason why it is more economical to transmit electric power at high voltage and low current than at low voltage and high current.
4. Why will transformers not operate if steady DC is furnished for the primary coil?

11.8 The Energy Picture Today

1. Why is there growing concern about the energy future of the United States and the world?
2. How is the energy used by the United States economy distributed among the different sectors?
3. Where does the energy used by the United States economy come from?
4. Why is there concern about these energy sources, and what are some of their other disadvantages?

11.9 Conservation

1. Why isn't nuclear fission energy at present the answer to our energy needs?
2. What limits the efficiency of electric power plants? How efficient are they at best?

3. What are the current possibilities and prospects for reducing waste energy in personal transportation?
4. Where does the ultimate decision lie regarding conservation of energy resources?

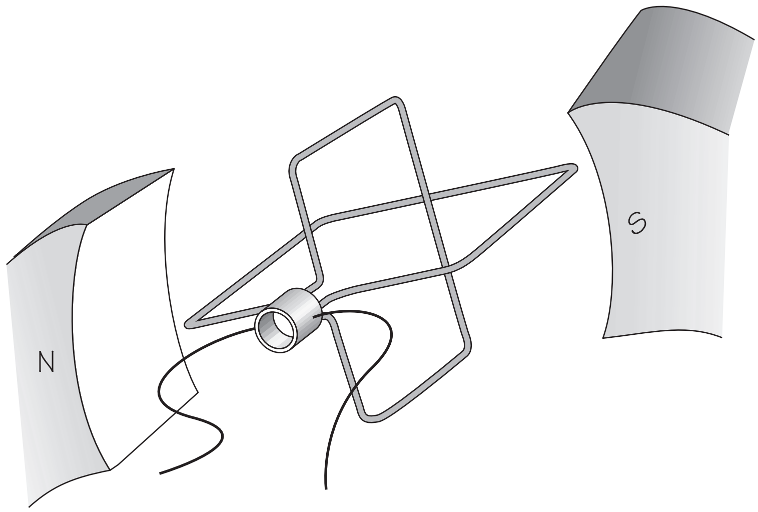
11.10 Renewable and Alternative Energy Sources

1. List all of the various energy options discussed in this section. Describe what each one entails in your own words.
2. Using your list of energy sources in Question 1, indicate the following:
   (a) Which ones are renewable and which are not?
   (b) Which ones involve direct production of electricity?
   (c) Which ones can provide heat and light without the use of electricity?
   (d) Which ones can provide the mechanical work to run a generator?
   (e) Which ones can provide the heat to create steam to generate electricity?
3. Using your list in Question 1, list the advantages and disadvantages of each of these energy sources.
4. Why haven't any of these alternatives replaced fossil fuels as the main energy source for advanced industrial economies?

DISCOVERY QUESTIONS

1. During the course of 1 day, try to take careful note of all of the electrical appliances and devices that you use. Then try to imagine what your life would be like if none of these devices existed.
2. During the course of 1 day, try to take careful note of all of the different ways in which you use energy. Note also the types of energy you use. Then try to imagine what your life would be like if the only energy you could use is what you could obtain only from food and the natural environment.
3. What sources of energy were there for industry before the electrical age? How was the energy transported to where it was needed?
4. Oersted discovered that a magnetic needle was affected by a current. Would you expect a magnetic needle to exert a force on a current? Why? How would you detect this force?
5. In which of these cases will electromagnetic induction occur?
   (a) A battery is connected to a loop of wire that is being held near another closed loop of wire.
   (b) A battery is disconnected from a loop of wire held near another loop of wire.
   (c) A magnet is moved through a loop of wire.
   (d) A loop of wire is held fixed in a steady magnetic field.
   (e) A loop of wire is moved across a magnetic field.
6. It was stated on page 516 that the output of a DC generator can be made smoother by using multiple windings. If each of two loops set at an angle were

connected to commutators as shown, what would the output current of the generator be like?



7. Trace the energy conversions in a system of a generator and motor, from heat input to work output. In what ways are the first and second laws of thermodynamics obeyed?
8. Why is a generator coil harder to turn when it is connected to an appliance to which it provides current, such as a lamp, than when it is disconnected from any appliance?
9. Suppose two vertical bar magnets, each held by one end at the same level, are dropped simultaneously. One of them passes through a closed loop of wire on the way down. Which magnet reaches the ground first? Why?
10. Comment on the advisability and possible methods of getting out of a car over which a high-voltage power line has fallen.
11. Using the data given in Section 11.8, compare the amount of energy required for the subsistence of an average human being per day with the amount of energy consumed per person per day in the United States. How would you account for the difference?
12. For each of the sources of energy listed in this chapter list the advantages and disadvantages.
13. On the basis of this chapter, and your own readings, how would you assess the outlook for the world's future energy needs? How would you assess the outlook for the available solutions, namely other energy sources and conservation?
14. Look up the history of a recent new technology, such as the Intel processor or Microsoft's computer operating systems, or a successful Internet company, and compare their sources and strategies for success with Edison's.
15. This chapter has described several instances in which science, technology, and society have interacted with each other. Summarize some of these interactions

and notice any similarities and differences. Can you draw any conclusions from this?

16. This chapter has described several great technological breakthroughs associated with fundamental scientific discoveries. Make a list of some of these discoveries and breakthroughs, then list the benefits to humankind as well as any real or potential detriments. In each case what are the respective responsibilities, if any, of the scientists, the engineers, the industries, the governors, and the general public in ensuring that the detriments are avoided and the benefits are achieved?